The Milky Way and the Local Volume

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Executive summary

Understanding the structure, formation history and stellar content of the Milky Way has rapidly grown into one of the central fields of astrophysics world-wide. The quality and quantity of data that allow us to make the Galaxy a model organism for understanding galaxy formation as well as stellar populations and stellar physics, continues to grow exponentially. Through its strength in stellar and galaxy formation theory, its strong role in ground-based initiatives and Gaia, the German community has achieved a role of global importance, and is well-positioned to attain a role of global leadership.

To realize this potential, it is crucial that suitable long-term funding schemes are being made available for Milky Way research. In particular, a critical mass for data science, data calibration, and modeling must be built across the German community. On shorter time scales, high priority should be given to preparing for the exploitation of the Gaia data, and complementary ground-based spectroscopy. To be able to expand their leading role in this research field, it would be desirable for the German community to have a broader access to telescopes in the northern hemisphere.

1. Key questions in the field today

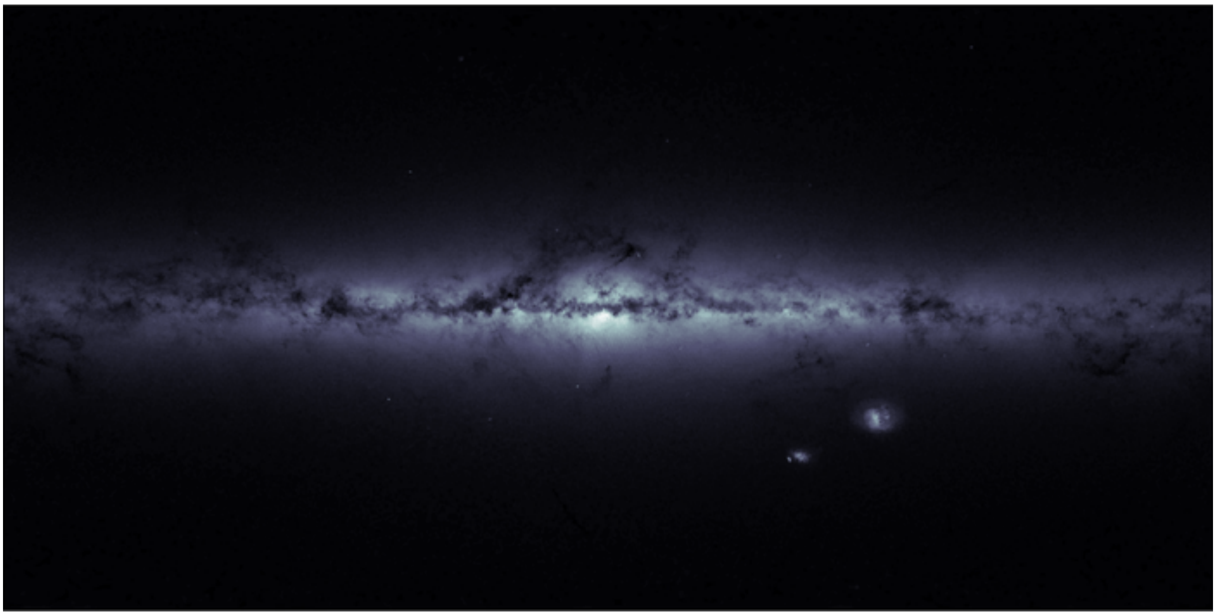

Figure 1: This image, based on housekeeping data from ESA's Gaia satellite, portrays the outline of our Galaxy, the Milky Way, and the Magellanic Clouds. It was obtained by plotting the total number of stars crossing Gaia's focal plane per second; i.e., this is a measure of the density of stars in the region that is being scanned. With Gaia and large spectroscopic surveys, we will finally start to fully understand the Milky Way as a galaxy, leaving the very local Hipparcos volume, and obtaining exquisite chemical and kinematical information for a large portion of the Galaxy. Credit: Gaia/ESA

The field of research on the Milky Way system and Local Volume (i.e. within a distance of 12 Mpc from us) is currently in a transformative phase, because unprecedented observational details that can now be obtained for large samples of objects throughout the Milky Way and some of its satellites, including rare stars such as those at low metallicity. The number of stars for which spectra of excellent quality are available has been growing exponentially, and this trend will continue into the next decade. Hence one of the main common points in the feedback received from the community was that thanks to the much larger body of data to be explored (and Gaia plays a key role in this context; see Figure 1 for an illustration), we expect a much better understanding of stellar evolutionary channels or rare populations in the Milky Way context. On the other hand, the community has raised the concern as to whether we are ready to fully exploit the Gaia data, and related follow-up spectroscopy, with state-of-the-art theoretical models.

The following key questions to be answered in the next 10-15 years were identified:

- The Galaxy in a cosmological context: what is the formation and evolution history of the Milky Way and its Local Group environment?
- What was its cosmic gas accretion history? What determined its high baryon fraction? Which processes regulate its star formation history and its composition of hot and cold gas? How is star formation initiated?
- How much formation history has our galaxy retained (radial migration in the disk, mergers)? To which extent can we reconstruct its chemo-orbital pre-history? Are we able to construct a global structural and dynamical model for the Milky Way? And in this context, where was the Sun born?
- What is the contribution of the Magellanic Clouds to the Milky Way halo? How were their history and structure shaped by their interaction, and under the influence of the Galaxy?
- Distribution of satellites and streams in the Milky Way halo (constraints to dark matter – DM – and Lambda Cold Dark Matter – LCDM): can LCDM simulations explain the Planes of Satellites around our galaxy and M31? Are there empty dark matter halos?
- Are there abundance signatures in the oldest stars of the Milky Way system that point towards Population III?
- How are the evolution of the stellar halo, the stellar disk components, and the bulge related?
- How shall we use star cluster populations across the galaxy types in the Local Volume to probe the different processes? One can look e.g. for differences and commonalities in abundances, formation times, survival, and dissolution.
- Do we understand the cause of multiple stellar populations in globular clusters?
- What are the Solar neighborhood data telling us in terms of reference objects for surveys of larger volumes: masses, ages, chemical abundances, stellar multiplicity?

2. Key results of the previous decade

Germany already has a leading role in addressing some of the questions listed above. In particular, there have been prominent achievements of the German research groups, as for instance (the list is not exhaustive):

- Construction of the first realistic dynamical models of the Galactic bulge and bar, as well as the first global models of disk dynamics.

- First quantitative estimates of the impact of radial migration in the Milky Way disk, and predictions that were confirmed with spectroscopic data.
- Completion of the RAVE survey with radial velocities for almost half a million stars.
- Approval by ESO of the German-led 4MOST facility, which will provide a massive Gaia spectroscopic follow-up of the Milky Way and Magellanic Clouds stars, as well as of Local Volume galaxies.
- Generation of important constraints on the origin of the stellar disk components, both from modeling and data (including the first use of asteroseismic data for Galactic Archaeology).
- Measurement of the mass of the stellar halo of the Milky Way, and detection of halo substructure, with various stellar tracers.
- Discovery and characterization of the faintest, least massive dwarf galaxies ever detected.
- Accurate measurement of the mass of the black hole in the Galactic center.
- Discovery and characterization of most metal-deficient stars in the Milky Way and its satellites.
- Mapping of the Milky Way in nucleosynthesis and cosmic-ray illuminated gas, in annihilation gamma-rays from positrons, and in high-precision HI. These observations have shown that the Galaxy's gas is rather structured, and probably reflecting complex transport processes complementary to stellar information.

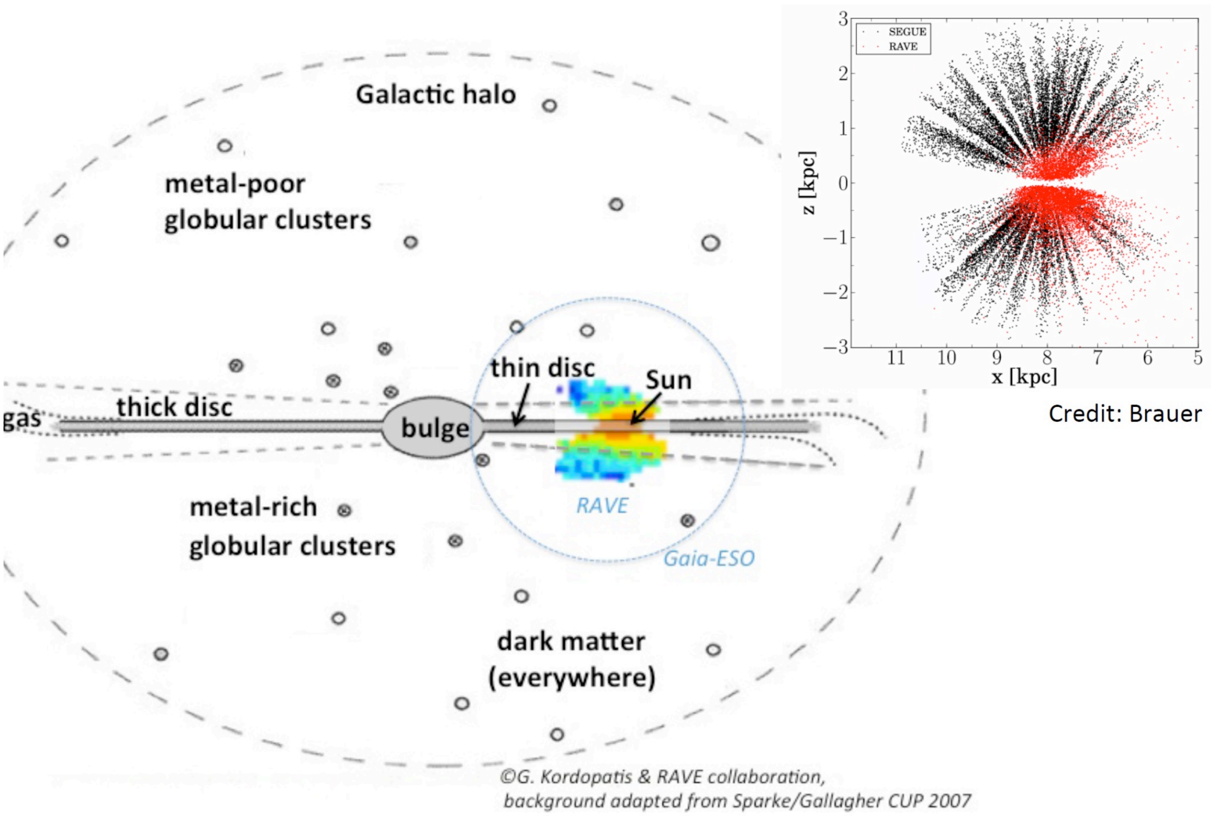

Figure 2: Survey volumes of the RAVE and Gaia/ESO surveys.

3. Key questions for the next decade

The community is convinced that one of the major challenge will be the development of a fully interdisciplinary approach when addressing questions regarding the assembly history of the Milky Way. It is becoming clear that the classical picture of our galaxy, divided into a thin disk, thick disk, bulge and halo, will lose sense once a more detailed view, as the one presented by Gaia, will be available. This will in turn lead to the necessity to model the Milky Way (and galaxies in general) at a level of detail compatible with the quality of the Gaia data (plus complementary ground-based spectroscopy). However, simulating the formation and evolution of a Milky Way-like galaxy from first principles is not an easy (or even feasible) task at present. At best, a suite of Milky Way look-alikes (depending on the criteria one adopts) will be available. Moreover, disk asymmetries and non-equilibrium processes preclude the use of stationary dynamical models. In other words, dynamics needs to be taken into account self-consistently. And finally, dynamical information alone is not sufficient, as stars move away from their birthplace (i.e., migrate), and only detailed chemistry will allow the detection of intruders (or migrated stars) into selected samples.

On the other hand, the mixing of stars from different Galactic regions can also be seen positively. Gaia will have high-precision access only to a relatively small part of the Galaxy, but thanks to mergers and radial migration, stars from different radial bins will be connected but not thoroughly mixed. This offers a unique opportunity to study stars born far way (where the Gaia data is less precise) in great detail if they appear near to us, and we learn about the whole galaxy even if the best data is confined to a smaller region.

It is hence possible to summarize the main goals for the next 10-15 years as follows:

- make competitive use of abundant new spectroscopic surveys, Gaia and asteroseismology (CoRoT, Kepler, K2, and the future Plato mission);
- develop rigorous techniques that link spectroscopy, astrometry and asteroseismology;
- compare the above dataset with state-of-the-art chemodynamical models of the Milky Way in the cosmological framework;
- use the chemical and kinematical information to fully chart substructures in the disk, halo and bulge of the Galaxy;
- understand the interaction with satellites and Local Group galaxies;
- understand the interstellar matter cycling, gas accretion and mixing timescales in the interstellar matter;
- trace the structure and dynamics of spiral arms and bar in the Milky Way, which turns out to be critical to understand processes such as radial mixing;
- produce cosmological simulations of a Milky Way-like galaxy and of the Local Group;
- understand the implications of the detailed evolution history of the Milky Way on galaxy formation and evolution in general.

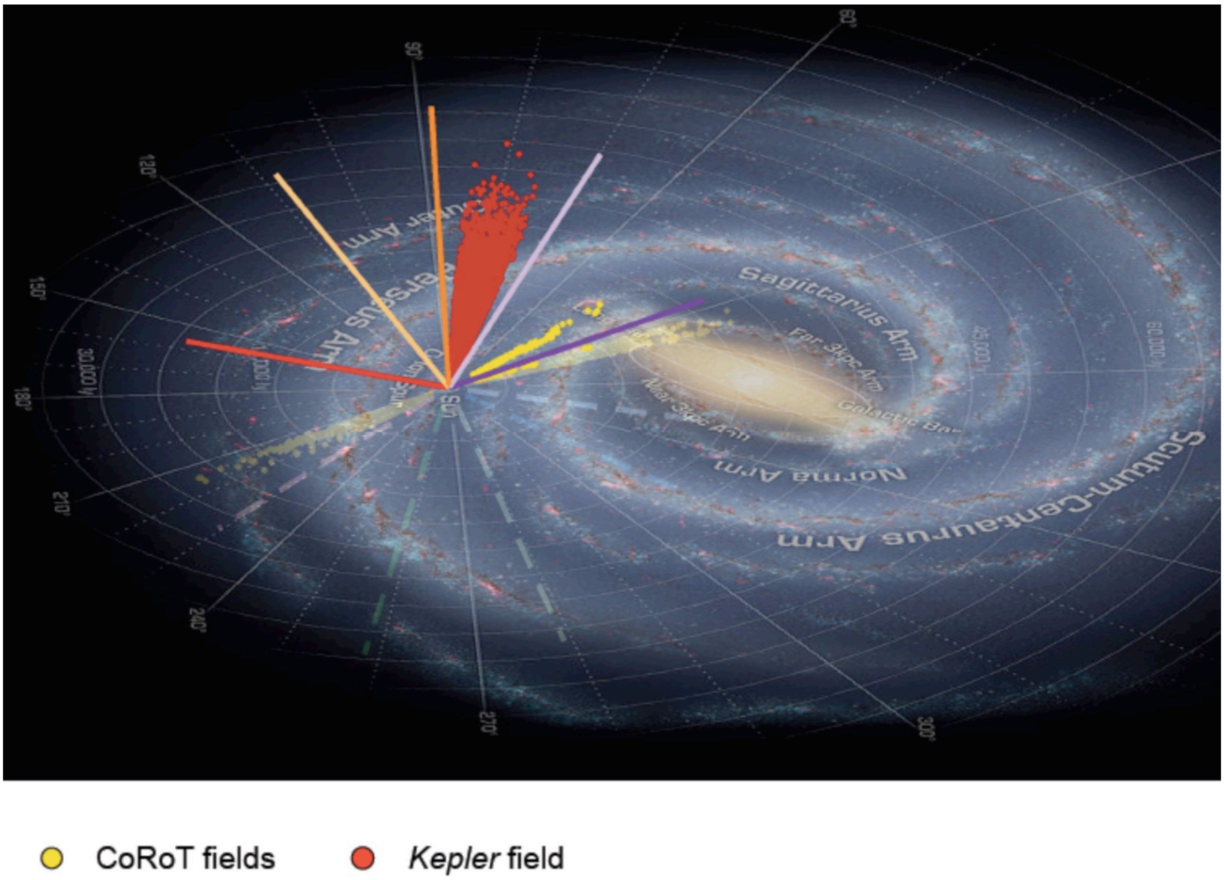

Figure 2: The CoRoT and Kepler fields.

4. Particular role and strengths of the research community in Germany

We will now investigate the position of the astrophysical research groups in Germany with respect to answering the above questions, and where is Germany particularly visible internationally. The self-assessment of the German community active in Milky Way and Local Volume research is that compared to similar communities abroad, the German community is strong and well integrated into the German research environment, as well as into international research networks.

There are several research areas in which German research groups are leading world-wide, such as the structure and dynamics of the bulge and bar of the Galaxy; chemo-dynamics of the Galactic disc; study of the Magellanic Clouds; discovery and analysis of Milky Way satellites; Galactic center research; dynamics and formation of star clusters; chemical tagging by means of spectroscopic surveys; modeling of the interstellar medium; measurement of elemental and isotopic abundances of stars; cosmological simulations of Galaxy formation; and simulations of the formation of the first stars.

Several institutions have a long-standing experience and a leading role in designing and building instruments for the largest, ground-based optical and near-infrared telescopes as well as for space missions, such as Gaia and Plato. This is important e.g. for influencing the designs of these instruments such that Milky Way science can be carried out with them, and for privileged data access.

5. Key infrastructure needed for researchers in Germany

5.1 Funding

By international standards, the relevant research groups in Germany are in general sufficiently funded, thanks to suitable schemes of the organizations providing third-party funding (DFG, BMBF, DLR, Humboldt Foundation, DAAD, and ERC), and base funds supplied by the institutions hosting these research groups (i.e., universities, Max Planck institutes, and Leibniz institutes).

The funding situation is critical in establishing and maintaining a community with broad expertise in theory, observations, numerical simulations, and instrumentation. It also allows German institutions to successfully compete on the international job market, leading to a constant flow of well-qualified PhD students and postdocs. High-profile researchers can be attracted e.g. through the Emmy Noether program of the DFG, Max Planck research groups, the Sofja Kovalevskaja program of the Humboldt Foundation, and Humboldt Professorships.

Of particular importance are long-term funding schemes such as Collaborative Research Centers (SFBs) of the DFG, enabling e.g. a proper scientific exploitation of large datasets; e.g. the data currently being collected by Gaia. For example the SFB 881 “The Milky Way System” established in Heidelberg in 2011, which is currently in its second funding period, has considerably strengthened Milky Way research in Germany.

It is also important to ensure a flexible infrastructure that in this framework leaves room for unpredictable initiatives.

5.2 Sky surveys and related issues

Participation or leading roles in wide-angle sky surveys (e.g., SDSS, Gaia-ESO, PAndAS, Pan-STARRS, RAVE, LAMOST) was crucial for past achievements, and will continue to be important in the future. The expertise for reducing, calibrating and analyzing data collected by such surveys is currently distributed over several institutes in Germany. Moreover, personnel for these tasks is typically hired only for periods that are short compared to the timescale for preparing and conducting these surveys, which can lead to the loss of knowledge. It has therefore been strongly suggested by the community that this expertise should be concentrated in national astronomical data science centers. Models for such centers already exist in other countries; e.g., the CASU Astronomical Data Centre in the UK, or the Terapix center in France.

For the best possible scientific exploitation of the aforementioned as well as future surveys, more resources should be devoted to chemo-dynamical modeling of the Galaxy. To provide a solid basis for Galactic archaeology studies, it is also necessary to better coordinate spectroscopic sky surveys in both hemispheres, current and future asteroseismology projects (CoRoT, Kepler, K2, Plato), and research in stellar evolution.

Furthermore, interpretation of chemical abundance data requires input from nuclear physics. It is therefore important to coordinate the efforts in this area within Germany, also in view of large infrastructure investments such as the Facility for Antiproton and Ion Research (FAIR)[1].

[1] http://www.fair-center.de/

5.3 Telescope access

It is of utmost importance that research groups in Germany continue to have access to ESO telescopes including ALMA and the future E-ELT. Access to SKA is strongly desired.

While access to ground-based telescopes in the southern hemisphere is generally very good, and a broad range of highly competitive instruments exists or are being planned, telescope access in the northern hemisphere is limited at least for the broader community. In particular, a large majority of the German community can access 8m-class telescopes in the northern hemisphere equipped with high-resolution optical and near-infrared spectrographs only through international collaborations. The situation is similar for wide-angle multi-object spectrographs such as WEAVE.[2]

Several new facilities will become available in the next decade that increase the quality of data with respect to sensitivity, spatial resolution, and frequency within a broad wavelength range. The German community is already/ or plans to be actively involved in the development and preparations of LSST, Euclid, and JWST operations (the latter via ESA). These facilities will allow German scientists to study, for example, stellar populations in the Local Group galaxies and beyond with an unprecedented level of detail. It will be possible to study for the first time the resolved stellar content of galaxies at the edge of the Local Volume increasing the parameter space sampled by these objects (galaxy type, metal content, history, and environment) and draw firm conclusions on the links with our more immediate neighborhood.

A strong worry is that high-resolution spectroscopy of the near UV from space will not be possible anymore once HST has been decommissioned. This spectral range is crucial e.g. for determining the abundances of neutron-capture elements in stars. Hence it would be strongly desirable if Germany would participate in an initiative such as the High-Definition Space Telescope (HDST)[3], a 11.7m telescope conceptually developed by AURA.

Other telescopes and large-scale projects the German community wishes to be involved with are: SOFIA, Calar Alto, the LBT, and SDSS IV including APOGEE-South.

6. Summary and conclusions

The Milky Way and Local Volume field of research is entering a golden period characterized by the availability of Gaia data. This is going to revolutionize many aspects of research currently undertaken by the related groups that are already striving to prepare the terrain for the best possible exploitation of the data. Critical mass and continuity of expertise are key factors to guarantee a prompt return to the resources already invested into this area of research. Contemporary initiatives to foster our understanding of the environment and its substructures (i.e. other nearby galaxies) through the involvement in current and planned initiatives is fundamental to establish a link with the near Universe and to extrapolate the knowledge gained to other objects and fields.

[2] http://www.ing.iac.es/weave/
[3] http://www.hdstvision.org/