

Stars Without Borders: Radial Migration in Spiral Galaxies

May 21-24, Medana, Slovenia

ESF-GREAT Scientific Summary & Report
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1 Summary

This was the first ever workshop dedicated to the topic of radial migration, which is a rapidly growing field in Galactic and extragalactic astronomy. In brief, radial migration relaxes the notion that stars in galactic disks orbit mostly at the same distance from the galactic center for their entire lives, which has been assumed for 30 years of galactic disk modeling. Instead, we now know that stars can change their radii rapidly by many kiloparsecs, implying that stars near the Sun, for example, are representing a rich mix of galactic locales. Our own Sun may also have migrated throughout the Galaxy before arriving at its current location, a notion that has potentially important consequences for solar system studies or even astrobiology.

The number of scientists actively grappling with radial migration has increased drastically over the past few years. This increase in interest comes none too soon: over the next decade, a staggering number of surveys (Gaia, HERMES, LSST, PanSTARRS etc.) will depend upon our understanding of the radial mixing process for the realization of some of their scientific goals. However, in order to make significant progress in the field, to move beyond single models and step into the arena of quantitative predictions, a concerted effort among observers and theorists needs to take place. The general consensus among the participants in the workshop seemed to be that some degree of radial mixing is required to explain certain facts about the Milky Way disk, but the extent of the mixing process is at present unknown.

Given that the implications of radial mixing cut across many sub-fields of astronomy, our goal for the workshop was to try and represent a good cross-section of this diversity. The participants spanned the range from theoreticians and modelers of the Galaxy to stellar populations specialists and extragalactic observers. We divided the workshop into five themes: theory; modeling; evidence and constraints from local stellar populations; the future of stellar parameters; and extragalactic observations. Each session was followed by a 30-minute discussion period. The workshop was attended by 40 participants from European, north american, and Australian institutions. 19 of the attendees were junior scientists, 11 of them students. The students paid no fees for their local expenses, which included room, board, the costs of conference room and coffee breaks.

2 Scientific Content

We were fortunate to have the support and guidance of a Science Organizing Committee: J. Binney (Oxford), R. de Jong (Potsdam), K. Freeman (Mt. Stromlo), G. Gilmore (Cambridge), A. Helmi (Groningen), H. Morrison (Case Western Reserve), R. Schönrich (Ohio State), J. Sellwood (Rutgers), T. Zwitter (U. of Ljubljana).

The scientific program was split into five sessions. Each speaker was given a total of 30 minutes including questions. I summarize the main topics and results in turn below.

- Theory & Simulations

The properties of spiral structure in galaxies are generally poorly understood. Although many simulations seem to produce transient spirals, we presently lack a predictive theory that would allow us to establish observationally whether structure in real galaxies, and in particular the Milky Way, is also transient. Partly due to the relevance of this question a new wave of effort to understand spiral structure is underway. Sellwood, D’Onghia, and Grand presented very different results from simulations: while Sellwood argues for transience, D’Onghia finds that very steady patterns can be excited by fluctuations in the disk, and Grand described so-called co-rotating spiral arms which were transient, but also had the peculiar properties of changing their pattern speed as $1/R$. Certainly much in the study of disk structure is affected by numerics; we can only hope that given increasing computing power we will soon come closer to convergence.

Much work is being done trying to understand the mixing process in N -body simulations. Where single simulations were used in the past to provide a set of constraints, suites of simulations are being used now to study a variety of effects. One of the most important ones is certainly the influence of perturbers/mergers. An important recent development was reported by Solway, who finds that the mixing process can continue also in the thick disk. However, the community still lacks a smoking-gun prediction or property that migration produces which would otherwise be absent. Certainly no current observational evidence is in stark conflict with results from radial migration studies.

- Modeling

A clear path forward is the fusion of analytic chemical evolution modeling and the fully 3D simulation approach. They need to inform one another, and this need was stressed by both Prantzos and Chiappini, both veterans of the chemical evolution modeling community. Analytic chemical evolution models are an efficient way to probe large swaths of the available parameter

space, that is otherwise unreachable by simulations. Tolfree presented work-in-progress that is trying to characterize the mixing process using analytic theory. The goal is to provide simplified constraints on the maximum radial excursions expected as a function of spiral amplitude and pitch angle. This is a crucial new development because it could provide a framework to bridge the gap between analytic modeling and 3D simulations.

- Evidence and Constraints from Local Samples

Rix, Bovy, and van de Ven discussed new results from the SEGUE survey (a part of SDSS-III) regarding the structure of the Milky Way disk. The quantity and quality of data from SEGUE, which allowed for structural fitting of individual stellar populations based on their detailed chemical properties, provides an both an interesting glimpse of the future and inspiration for those making theoretical predictions. Haywood argued that while some properties of locally-observed stellar populations are impossible to explain without radial mixing (i.e. metal-rich intermediate age stars), other details of kinematics-metallicity space may not be adequately represented by current models. However, it appears that state-of-the-art data is consistent with there being a metal-poor, large scale-height population that also has a *short* scale-length. This is contrary to what has usually been assumed (and derived!) for the scale length of the canonical thick disk.

An important theme that recurred during the discussions in this session was that the community was very interested in exploring the Milky Way disk beyond the Solar Neighborhood. The SEGUE data makes this possible to a limited extent already, but Gaia in particular will give us a detailed view of the outer disk where it might be easiest to see a signature of the mixing process might be. This should serve as a clear signal to the theorists that predictions targetting other regions of the disk need to be ready for the next wave of data.

- Future of Stellar Parameters

The theme of the "future" was increasing both the accuracy of age determinations as well as the samples for which at least approximate ages are known. Freeman presented a new spectroscopic survey based on a sub-sample of the Geneva-Copenhagen survey, chosen specifically to allow for a cleaner derivation of ages. The goal is to update the current state-of-the-art of the local age-metallicity-velocity relation. Soderblom provided a much-needed update and review of the current state of age determinations, in particular for the older populations. Determining stellar ages to 10% via asteroseismology is a tantalizing prospect and current samples count dozens of stars already using data from the Kepler mission.

Moving from absolute accuracy toward larger sample sizes, Zwitter presented

a possible application of the RAVE dataset. By using chromospheric activity as a relative age indicator, samples could be split into approximate age groupings. Such an approach would not allow for absolute measurements of star formation rates, for example, but it could be used to better understand gross structural trends in the Milky Way disk.

Finally, much discussion was devoted to chemical tagging, with Bland-Hawthorn presenting the details of the upcoming HERMES survey (a fiber-fed multi-object spectrograph) and de Jong discussing the plans for the 4MOST project (similar to HERMES but with a broader spectral range and coarser resolution). It is fascinating that several chemical tagging studies (where stars can be grouped according to their chemical and kinematic properties) have already been done (de Silva). Much effort is being done for the preparations for the Gaia mission and potential chemical tagging applications (Martinez).

- Extragalactic

Another somewhat surprising message from the meeting was that the community was once again interested in pursuing the outer disks of *other* galaxies to constrain the radial mixing process. It is a fact that with the onset of incredible new surveys such as the Integral-Field-Spectroscopy (IFU) survey CALIFA (Ruiz-Lara), which will provide a sample of ~ 60 spiral galaxies. Yoachim presented the first results from another similar study, which used an IFU to yield profiles of metallicity and age gradients. Importantly, for many galaxies in their sample the signal-to-noise was high enough to obtain the gradients well into the outer disk, beyond the break in the surface brightness profile. Radburn-Smith presented yet another complementary study, this time using Hubble Space Telescope data to derive stellar population properties well into the far-outer disk of several nearby disks. They used resolved-star color-magnitude diagram fitting techniques to derive the population properties, and compared the observed stellar population trends with model predictions, finding generally good agreement and tentative confirmation of the radial migration predictions for the outer disks.

3 Impact

The workshop will not have a published proceedings but we have made almost all of the talks freely available on-line at the workshop website:

http://www.itp.uzh.ch/~roskar/migration_workshop/

As stated above, the workshop reaffirmed the belief in the community that some degree of radial mixing is required to explain parts of currently known observational facts about the Milky Way and in particular about the solar neighborhood. The open question is to assess the importance of the process in our own Galaxy as

well as other systems. The workshop through its varied, both in field of expertise and in stature, participants sends a clear signal to the astronomical community at large that this is an extremely relevant topic, which needs to be addressed.

While during the infancy of radial migration studies theory kept ahead of observations and informed the direction of observational inquiries, we are now in a position where theory has fallen somewhat behind. The workshop brought into focus a clear need for detailed theoretical predictions in the full chemodynamical space. We do not need to wait for Gaia or other future surveys to start these comparisons: the SEGUE results have clearly shown that this work can commence immediately. Part of what is needed are robust methods for bringing the simulations into the observed space. By doing this work now, the models will be ready for the next generation of observational surveys, such as Gaia, and in a position to extract and inform the science gleaned from those datasets.

Two other important results emerged from the workshop. First, in the Milky Way high-quality data are becoming available to allow for detailed studies of stellar populations in *other* parts of the disk away from the solar neighborhood. Trends that will emerge here will undoubtedly push current models and require their further development. Second, extragalactic observations of nearby systems should be used in concert with Milky Way in the pursuit to understand the relative importance of the mixing process to other, cosmologically-relevant processes such as gas infall and merging events. We look forward to future developments in these topics.

“Stars Without Borders”

Radial Migration in Spiral Galaxies

May 21-24, 2012

Workshop Program

Sunday, May 20

18:30 - 19:00 Shuttle transport from accommodations to Belica for welcome drink
20:30 - 22:30 Dinner

Monday, May 21

8:30 - 8:50 Shuttle transport to Belica
9:00 - 9:05 Welcome and practical information
9:05 - 9:30 Ken Freeman: Workshop Introduction
9:30 - 10:00 Jerry Sellwood: The Origin of Transient Spiral Structure
10:00 - 10:30 Elena D'Onghia: Long-lived self-sustaining spirals
10:30 - 11:00 Robert Grand: Co-Rotating Spirals
11:00 - 11:30 *Coffee Break*
11:30 - 12:00 Michael Solway: Radial Migration in Thickened Disks
12:00 - 12:30 Paola Di Matteo: Radial Migration in Simulations
12:30 - 13:00 Daniel Pfenninger: Radial Diffusion in Barred Galaxies
13:00 - 14:30 *Lunch*
14:30 - 15:00 Ivan Minchev: The effect of radial migration on disk heating
15:00 - 15:30 Rok Roškar: Radial migration in growing disks with/without mergers
15:30 - 16:00 Jonathan Bird: migration and minor mergers
16:00 - 16:30 *Coffee*
16:30 - 17:00 Sarah Loebman: Chemodynamical trends in simulations
17:00 - 17:30 Daisuke Kawata: Observational consequences of corotating spirals
17:30 - 18:00 Javiera Guedes: Migration in Cosmological Simulations
18:00 - 18:30 Theory Discussion
19:00 - 22:30 Wine tasting in the Dobrovo Castle cellar followed by dinner

Tuesday, May 22

8:30 - 8:50 Shuttle transport to Belica
9:00 - 9:30 Nikos Prantzos: impact of radial migration on chemical evolution
9:30 - 10:00 Cristina Chiappini: chemical modeling
10:00 - 10:30 Ralph Schönrich: chemical modeling with radial mixing
10:30 - 11:00 Paul McMillan: Torus modelling & Migration

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| 11:00 - 11:30 | <i>Coffee</i> |
| 11:30 - 12:00 | Mark Gieles: Open cluster dispersal |
| 12:00 - 12:30 | Andreas Just: Combining disk models with Rave and SEGUE data |
| 12:30 - 13:00 | Katy Tolfree: Constraints on spiral-induced mixing |
| 13:00 - 13:30 | Discussion on Modelling |
| 13:30 - 15:00 | <i>Lunch</i> |
| 15:00 - 15:30 | Sofia Feltzing: Stellar migration -- local evidence? Gaia-ESO update |
| 15:30 - 16:00 | Misha Haywood: evidence of stellar migration in local samples |
| 16:00 - 16:30 | Birgitta Nordström: Signatures of accretion in the solar neighborhood |
| 16:30 - 17:00 | <i>Coffee</i> |
| 17:00 - 17:30 | Hans-Walter Rix: How (Not) to Dissect the Milky Way's Disk |
| 17:30 - 18:00 | Jo Bovy: SEGUE observations of the Milky Way disk |
| 18:00 - 18:30 | Glenn van de Ven: The mixed origin of the Milky Way disk from SEGUE |
| 18:30 - 19:00 | Discussion on local evidence or lack thereof for migration |

Wednesday, May 23

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| 8:30 - 8:50 | Shuttle transport to Belica |
| 9:00 - 9:30 | Ken Freeman: the Age-Metallicity-Velocity relation |
| 9:30 - 10:00 | David Soderblom: stellar ages through asteroseismology |
| 10:00 - 10:30 | Tomaž Zwitter: Age indicators in large spectroscopic datasets |
| 10:30 - 11:00 | <i>Coffee</i> |
| 11:00 - 11:30 | Joss Bland-Hawthorn: HERMES |
| 11:30 - 12:00 | Roelof de Jong: 4MOST |
| 12:00 - 12:30 | Discussion about the future of stellar parameters |
| 12:30 - 20:30 | Afternoon activity |
| 20:30 - 22:30 | Workshop dinner |

Thursday, May 24

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| 8:30 - 8:50 | Shuttle transport to Belica |
| 9:00 - 9:30 | Gayandhi De Silva: chemical tagging application to Argus association |
| 9:30 - 10:00 | Carmen Martinez: Migration and dissolution of open clusters and the search for the Sun's siblings |
| 10:00 - 10:30 | Judit Bakos: Extragalactic unresolved photometry/stellar populations with SDSS and follow-up observations |
| 10:30 - 11:00 | <i>Coffee</i> |
| 11:00 - 11:30 | Joel Roediger: Stellar populations of Type I/II disk galaxies |
| 11:30 - 12:00 | Tomas Ruiz-Lara: Stellar populations in the outskirts of spiral galaxies using IFU CALIFA data |
| 12:00 - 12:30 | Peter Yoachim: IFU observations of disk breaks |

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| 12:30 - 13:00 | David Radburn-Smith: Resolved stellar populations in outskirts of disk galaxies |
| 13:00 - 13:30 | Discussion on extragalactic observations |
| 13:30 - 14:00 | Conclusion |
| 14:30 - 16:00 | Lunch |

Stars without borders

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Co-Chairs

Rok Roškar, Institute for Theoretical Physics, University of Zürich
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Local Organizing Committee

Rok Roškar, ITP, University of Zürich
Tomaž Zwitter, University of Ljubljana
Maruša Žerjal, University of Ljubljana
Janez Kos, University of Ljubljana

Speakers

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|---------------------|------------------------------|---|
| Judit Bakos | IAC | Deep observations of disk outskirts |
| Jonathan Bird | Ohio State University | Migration with minor mergers |
| Joss Bland-Hawthorn | University of Sydney | HERMES and Workshop summary |
| Jo Bovy | Institute for Advanced Study | New constraints on the Milky Way thick disk |
| Cristina Chiappini | Potsdam | Chemical evolution |
| Elena D'Onghia | Harvard CfA | Long-lived spiral structure |
| Roelof de Jong | Potsdam | 4MOST |
| Gayandhi De Silva | AAO | Chemical tagging in the Argus association |
| Paola Di Matteo | Observatoire de Paris | Radial mixing in N-body simulations |
| Sofia Feltzing | Lund Observatory | Local observations and Gaia-ESO survey |
| Ken Freeman | Mt. Stromlo Observatory | The Age-Metallicity-Velocity relation and workshop introduction |
| Mark Gieles | Cambridge University | Open cluster dispersal |
| Robert Grand | University College, London | Radial mixing with Co-rotating spiral arms |
| Javiera Guedes | ETH Zürich | Mixing in cosmological simulations |

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| Misha Haywood | Observatoire de Paris | Evidence of mixing in local samples |
| Andreas Just | ARI Heidelberg | Combining disk models with Rave and SEGUE data |
| Daisuke Kawata | University College, London | Observational consequences of mixing around Co-rotating spirals |
| Sarah Loebman | University of Washington | The influence of mixing on chemodynamical properties of the disk |
| Carmen Martinez | Leiden Observatory | Migration and dissolution of open clusters and the search for the Sun's siblings |
| Paul McMillan | Oxford University | Radial mixing in Toroid modelling |
| Ivan Minchev | Astrophysikalisches Institut Potsdam | The Effect of Radial Migration on Disk Heating |
| Birgitta Nordström | Copenhagen University | Signatures of accretion in our galactic neighborhood |
| Daniel Pfenniger | Geneva Observatory | Radial diffusion in barred galaxies |
| Nikos Prantzos | AIP | The influence of radial mixing on chemical evolution |
| David Radburn-Smith | University of Washington | Observing migration in the outer disks of nearby galaxies |
| Hans-Walter Rix | MPIA, Heidelberg | How (Not) to Dissect the Milky Way's Disk |
| Joel Roediger | Queens University | The Stellar Populations of Type I/II Disk Galaxies |
| Rok Roškar | ITP, University of Zürich | Radial mixing in simulations with/without mergers |
| Tomas Ruiz-Lara | University of Granada | Stellar populations in the outskirts of spiral galaxies using IFU CALIFA data |
| Ralph Schönrich | Ohio State University | Chemical evolution with radial mixing |
| Jerry Sellwood | Rutgers University | Transient spiral structure |
| David Soderblom | STScI | Age determination with asteroseismology |
| Michael Solway | Rutgers University | Radial mixing in the thick disk |
| Kate Tolfree | Johns Hopkins University | Efficiency of radial migration in spiral disks |
| Glenn van de Ven | MPIA, Heidelberg | The mixed origin of the Milky Way disk from SEGUE/SDSS |
| Peter Yoachim | University of Washington | Beyond the Break: Observational Evidence of Stellar Migration from IFU observations |
| Tomaž Zwitter | University of Ljubljana | Identification of age indicators in large spectral datasets |

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