5.2 Open Issues in the Evolution of the Galactic Disks

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\textbf{Abstract}

Galactic disks pose a fascinating challenge both to observe and to understand. No realistic \textit{ab initio} formation models exist, so we are led by observations. However, many key physical processes affecting dynamics and chemical evolution can be isolated in kinematic and abundance data. Thus progress can be made by focusing on specific challenges with appropriate observations. We review some of the most topical here.

\textbf{Introduction}

The standard ΛCDM universe model is impressively consistent with a wide range of observations on large spatial scales (Komatsu \textit{et al.} \cite{2011}). Our understanding of the formation and evolution of galaxies in the ΛCDM context however remains very incomplete. Late-type spirals, like the Milky Way, in particular are extremely difficult to understand in the canonical hierarchical clustering paradigm (Shen \textit{et al.} \cite{2010}; Kormendy \textit{et al.} \cite{2010}). Recent detailed numerical simulations which attempt to form Milky Way-like galaxies require adoption of implausibly extreme and/or unusual conditions in the early history of the galaxy. A recent example among many is Guedes \textit{et al.} \cite{2011}, whose most observationally-plausible model requires an extreme star formation threshold, inconsistent with observations. More generally, Stewart \textit{et al.} \cite{2009} provide a detailed analysis of the challenges facing consistency between the best current models of late-type galaxies and observations. The primary challenge is that paradigmatic galaxy formation is necessarily hierarchical, with continuing mergers and accretion events for long times. Such mergers damage or destroy thin disks, forming bulges and/or thick disks. Thin disks should be rather rare and rather young. However, thin disks are observed to be common and old. Stewart \textit{et al.} \cite{2009} conclude “Our results raise serious concerns about the survival of thin disk dominated galaxies within the current paradigm for galaxy formation in a ΛCDM universe”. On smaller scales the challenges which models face in reproducing either the numbers (the Satellite problem), or the physical properties, of dwarf galaxies are well known. Recent sophisticated models include those of Sawala \textit{et al.} \cite{2011} and Parry \textit{et al.} \cite{2011}, which both conclude that current simulations differ by more than an order of magnitude from observations of real galaxies.

It remains unclear as yet to what extent the models lack an adequate approximation to the dominant physics, or if there is a problem in a common assumption, or both. The most likely common assumption to be inconsistent with the Universe is the extrapolation of the CDM power spectrum as a featureless structure-free power-law to arbitrarily small scales. There are many observational studies which show that small-scale dark matter potentials are cored rather than cusped (Gilmore \textit{et al.} \cite{2007}). It is plausible that the many challenges remaining in the standard model of particle physics imply a complex spectrum of elementary particles making up Dark Matter. Changing underlying assumptions in formation models in this way, led by observation, does however open a rich possible parameter space for exploration, which requires even richer observations to guide the process. We may conclude, as usual, that observations lead the way towards improved understanding. Progress in quantifying the observed properties of galaxies, and the Galaxy, and tensioning observations against (the limitations of) models, is the way in which our knowledge and understanding makes progress.

The observational properties of galaxy disks, including that of the Milky Way have been reviewed most recently by van der Kruit and Freeman \cite{2011}. Earlier major reviews which remain valuable include Gilmore, Wyse, and Kuijken \cite{1989} and Freeman and Bland-Hawthorn \cite{2002}.
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Figure 5.3: Normalized angular momentum distributions for the bulge (solid curve), the $r^{1/4}$ spheroid (short-dashed-dotted curve), the thick disk (long-dashed-dotted curve), and the thin disk (long-dashed curve).

Galactic Thick Disks

Thick disks seem to be a universal stellar population in disk galaxies. The extensive HST survey of Yoachim and Dalcanton [2006] showed that thick disks are present in all, or nearly all, disk galaxies. These thick disks make up typically 10 percent of the light of luminous (Milky Way-like) galaxies, and rather more, up to 50 percent, in lower luminosity systems. Interestingly, thick disk radial scale lengths are similar to those of the galactic thin disk, suggesting an association. Yoachim and Dalcanton [2006] further find that the thick disk stellar populations are typically old. Apparently thick disk formation is a normal aspect of the early formation of disk galaxies, an observation which requires explanation.

The Milky Way has a thick disk (Gilmore and Reid [1983]) with superficially rather typical properties. The stellar population which makes up the thick disk is apparently exclusively old, with age of order 12 Gyr, comparable to that of the metal-rich globular clusters (Unavane, Wyse, and Gilmore 1996; Jofre and Weiss 2011). The old age of thick disk stars is apparent even by visual examination of colour-magnitude diagrams from SDSS photometry of high-latitude fields (de Jong et al. 2010), where the sharp blue edge to the colour distribution is apparent.

This is a surprising result. As noted in the introduction, canonical hierarchical galaxy formation models have significant mergers continuing up to times corresponding to redshifts of order unity. These significant mergers should heat thin disks into thick disks, so that a wide age range in thick disks, and a bias to young ages in surviving thin disks, is anticipated (Kazantzidis et al. 2008, but see also Moster et al. 2010 for the importance of hard to model gas in these simulations).

Although thick disks are at least as old as the oldest stars which can be categorised as thin disk stars, there are structural similarities between thick and thin disks. Yoachim and Dalcanton [2006] establish these in external galaxies. In the Milky Way it has been known for some time that the distribution function of specific angular momentum of the Galaxy’s stellar populations shows that the thick and thin disks are in some way similar, while both the Bulge and the halo are systematically different, though similar to each other (Wyse and Gilmore 1992). The Wyse and Gilmore 1992 results are shown in Fig. 5.3. These results illustrate again the fundamental connection between thin disk and thick disk formation. The connection, if any between thick/thin disk and halo/bulge formation however remains problematic (Wyse and Gilmore 1992).

Evolutionary relationships are potentially complicated, given that, in addition to two types of disk,
Figure 5.4: The distribution of element ratios in a large sample of thick disk stars (red squares), and some halo (blue triangles) and thin disk stars (green), from a follow-up of the RAVE survey (Ruchti et al. [2011]). The stars are allocated to populations using kinematic criteria. Two features are worthy of emphasis: the thick disk stars extend to very low abundances; and the halo and thick disk stars obey the same correlation, with little scatter.

“thick” and “thin”, there are at least two types of bulge, “classic” and “pseudo”, [Kormendy and Kennicutt 2004], with the “pseudo-bulge” being itself closely related to the thin disk ([Fisher and Drory 2011], see also [Kormendy and Barentine 2010]), and probably formed from it by secular evolution. In this picture, thick disks predate thin disks which predate (pseudo-)bulges.

**Thick disk chemical abundances**

The volume-complete chemical element distributions functions as a function of kinematics, age, etc, or more simply, as a function of stellar populations, remain very poorly determined. The true distribution functions, sampled with understood bias, are primary data in understanding the coupled evolution of star formation locations and rates, gas flows, and later dynamical mixing ([Wyse and Gilmore 1995; Gilmore, Wyse, and Jones 1995; Gilmore and Wyse 1998]). In spite of substantial recent progress, such as SEGUE and RAVE, (eg [Burnett et al. 2011]), there is much to learn about the basic properties of Galactic stellar populations from the forthcoming large spectroscopic surveys, such as Gaia-ESO, HERMES, and APOGEE.

Most spectroscopic projects to date have been optimised to study the extremes of the distribution functions, eg, the very many surveys for very metal-poor stars, or very metal-rich stars. These surveys...
are however delivering impressive science. Among the most active relatively unbiased surveys at present is RAVE (Steinmetz et al. [2006]; Siebert et al. [2011]). Among the specific follow-up studies from RAVE, one has determined accurate chemical element abundance ratios for a large sample of stars with thick disk kinematic population assignment (Ruchti et al. [2010, 2011]). The fundamental result from this impressive study is shown in Fig 5.4. The striking feature is the similarity of thick disk and halo populations down to very low metallicity. This has important implications for invariance of the early stellar high-mass Initial Mass Function (IMF, cf Gilmore and Wyse [1991]) and the scale length of ISM mixing at early times. The extension of the metallicity distribution function to low values reduces the need for a significant precursor population (halo?) to pre-enrich the ISM which formed the thick disk. This further establishes the thick disk as a very early population in the galaxy. The thin disk, by contrast, lacks metal-poor stars (the infamous "G-dwarf problem"), and so cannot be among the first stellar populations to form in the proto-Galactic potential. Rather, the thick disk provides a natural explanation as thin-disk precursor, resolving the G-dwarf problem. The low metallicity of the (tail of) the thick disk is consistent with its old age (see above), and shows that radially very extended high-angular momentum populations existed at very early times (cf also Burnett et al. [2011]).

The Thin Disk

The immediate solar neighbourhood has been studied rather well, using field stars (e.g. Fuhrmann [2011]), while many star-count studies over many years have determined the approximate structural properties of the thin (and thick) disk (e.g. de Jong et al. [2010]). Among the more interesting current topics are the issue of radial chemical abundance gradients, the true dispersion in chemical abundances as a function of Galactocentric radius, and the big challenge of disk secular evolution.

The age-metallicity distribution function remains poorly determined, largely since ages for significant samples of (especially old) stars are extremely difficult to determine. We await Gaia precision distances with eager anticipation, to really advance on this front. In the interim however star clusters are a valuable probe. More cluster ages, metallicities and distances are highly desirable.

Clusters are also a valuable probe of galactocentric radial gradients. ISM studies, complemented by analyses of massive stars with good distances (Cepheids, and such like) suggest a fairly significant radial gradient is present today. Are these gradients also present in older stars? This question is of key importance in determining the importance of flows ("galactic fountains") driven by star formation, in the evolution of the disk. It is also key to test if secular evolution is important in the outer parts of the Galactic disk. Knowing both the amplitude of any radial abundance gradient, and the width of the local abundance distribution function, provides potentially interesting constraints on radial stellar mixing. Especially so if this information for old stars is feasible.

Secular evolution must be important in the thin disk. The disk is a mix of asymmetric time-dependent structures (spiral arms, bars,...) which perturb stellar (and cluster) orbits. These structures are especially important in the inner galaxy, apparently leading to pseudo-bulge formation, as noted above. There have been many recent suggestions that the secular evolution may be so strong it also significantly affects the outer Galaxy (Sellwood and Binney 2002; Schönrich and Binney 2009; Loebman et al. 2011). Only much improved observational limits, of both chemical abundances and the types of orbits which stars occupy as a function of age, can test these models. While we await Gaia, star clusters are the best option for progress here, since all of age, metallicity and distance can be determined.

Summary

We lack a predictive model of galaxy formation. Available models are so far from consistency with observation, and are so ad hoc, that we progress by observing. Fortunately, precision observations and large surveys are happening, with even better to come in the next few years, culminating with Gaia.

Thick disks provide robust evidence that large high-angular momentum disks were ubiquitous in the early universe. These disks are more extended vertically than are thin disks. Why? Did the disks form thick, or were they thickened?

Thin disks are common, radially large and vertically thin. Why have they not been destroyed by hierarchical mergers and accretions? Thin disks evolve secularly. In their inner regions this process is dominant. How important is it at much greater radii?
These - and many more - questions are the focus of current and new major surveys, where we confidently anticipate new progress, and new questions.

Bibliography


