# KEY QUESTIONS IN GALACTIC STRUCTURE WITH ASTROMETRIC ANSWERS

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ABSTRACT

Dynamical analyses, derived primarily from accurate distance and kinematic data, are the keystone to understanding the wealth of astrophysics in a galaxy. The Milky Way is believed representative of those giant spiral galaxies which dominate the luminosity of the Universe, thereby providing a touchstone for an understanding of galaxy formation and evolution. The dynamical evolution of a spiral galaxy is an extremely rich and wide ranging topic, crucial to all studies of galactic evolution. Precise astrometric data can uniquely determine the interplay between gravity and pressure, and the role of instabilities, in our Galaxy. Additionally, dynamical studies in the Milky Way are the only feasible high-precision experiment which can determine the spatial distribution of the ubiquitous dark matter, which apparently dominates the Universe.

The essential requirement for any serious astrophysical study of the Galaxy, and its contents, is that they be measured. Most of the stars, and almost all of the interesting dynamics, are found at low Galactic latitudes, in crowded fields, obscured by dust. Thus, there is an overwhelming scientific requirement for astrometric surveys to faint limiting magnitudes, probably in the near infrared, in very crowded fields, and where no blue-uv data are likely to be obtainable.

**Key words:** space astrometry, GAIA, Galactic Structure, Dynamics, Milky Way Galaxy, Galactic Evolution, Galaxies, infrared astronomy.

## 1. The Astrophysics of galaxies: *important and open questions*

Galaxies are today found with an extremely wide range of masses, sizes, luminosities, central densities, gas contents, chemical abundances and morphologies. Even in the Local Group, our own immediate cosmological neighbourhood, in which only about twenty galaxies are known, the masses of the known galaxies ranges over a factor of more than $10^5$, the range in luminosities spans a factor of $10^6$, the range of stellar space densities spans a range of $10^8$, the range of mean abundances of the chemical elements spans a factor of 100, while all possible combinations of stellar age distributions, from exclusively old to predominately very young, and all possible ranges of star to gas mass ratio, are seen. Perhaps the only common factor is that all are dominated by the ubiquitous but entirely mysterious dark matter, whose existence is deduced from stellar and gas dynamics.

This complexity is a reflection of the complexity and nonlinearity of the many physical processes that are relevant to the formation and evolution of galaxies. It is a considerable observational and theoretical challenge to elucidate the nature of, and the interplay between, these processes. Both detailed theory, incorporating such complex physical phenomena as gravitational and gas dynamics, star formation, and the energy balance of the inter-stellar medium, and sophisticated observations, especially kinematics, and critically near-infrared studies that penetrate the obscuring dust, are required in order to reconcile the present wealth of galaxy variety with a consistent and reasonably complete theory.

Fortunately, there are many fundamental aspects of the structure of galaxies that can be determined reliably from detailed analysis of the Milky Way Galaxy, and only from such analyses. Some of the observable properties of galaxies today retain a fairly direct fossil record of the conditions in the early universe at the time of galaxy formation (eg the present distribution of angular momentum), others are determined by the important physical processes during galaxy formation (eg correlations between chemical abundance and kinematics in old stars), while still others are determined by the distribution of the apparently ubiquitous 'missing' mass (eg the combination of stellar kinematics and the shape of the stellar system). Thus, detailed analysis of the kinematics, chemical abundances, and spatial distribution of the stellar populations and the inter-stellar medium in a typical large galaxy is a powerful means to study the important physical processes that dominated the formation and evolution of galaxies throughout the history of the Universe.

The physics of galaxy evolution has been studied in many ways for many years. The time is now ripe for a concerted attack for several reasons: purely theoretical dynamical analyses are only now, for the first time, reaching a stage of reality, sophistication and computational power such that they are capable of explaining real observational data. New observational capabilities, many relevant examples of which are now being commissioned – radio interferometers, infra-red surveys and satellites, wide-field multi-plexed stellar radial velocity survey spectrographs – are only now providing large samples of precise kinematic data. Models of the creation of the chemical elements are approaching the robustness and sophistication essential to match the wealth of new, high-precision, determinations of chemical abundances, in many galactic environments, made possible by new spectrographs and detector arrays. Innovative observational techniques - adaptive optics, new space missions, new large telescopes, multi-plexed spectrographs - allow specific tests of the predictions of available models in galaxies of all types, sizes, masses, ages and evolutionary histories.

This investigation requires a mix of complementary expertise, to obtain and to analyse data on the chemistry, kinematics, and spatial distribution of both stars and the inter-stellar medium, in its several phases, in a galaxy typical of those which dominate the luminosity of the Universe. A wide variety of observational data are required. The analysis requires complementary approaches, ranging from an applied-mathematical dynamics analysis, through idealised analytic models of chemical evolution of whole galaxies, into such detailed observational analyses as the specific contributions of evolved stars to the infra-red luminosity and chemical balance of the central regions of the Milky Way.

The basic questions on which astrophysics will focus for the next few decades, and which, critically, cannot be answered until a GAIA-like mission provides its answers, will include the spatial distribution of stars, chemical elements, and mass, in galaxies. The distribution of chemical elements is determined by a mix of the history of star formation, the relative number of stars of differing masses formed at different times, the relative time of formation of the different stellar populations, the spatial distribution of those populations, and the history of gas flows into and inside the galaxy.

The spatial distribution of stars, and the distribution of mass, are intimately linked, through the gravitational potential, and through the history of the star formation rate. When and where did bulge stars form? what causes disk warps? do disks undergo repeated cycles of bar instability? are bulges formed as a result of vertical instability during bar formation? what causes lopsidedness in so many disks? are all topics of active interest which may now be studied in detail for the first time.

The fundamental question of the distribution of dark matter, including the shapes and sizes of galactic halos, and crucial constraints on the nature of the dark matter, can be derived from detailed analyses of nearby galaxies. Crucially here, the smallest scales on which dark matter can cluster, and thus the only available limit on its temperature and phase space density, are uniquely studied through the stellar dynamics of the dwarf satellites of the Milky Way and precise determinations of the mass of the Galactic disk. An intriguing new technique for study of Galactic structure in the very complex inner regions, ideal to complement forth-coming infra-red surveys, has arisen from dark matter surveys. Gravitational microlensing studies, originally designed to measure the amount of dark matter in outer halos, are paradoxically providing a wealth of unique new data on the distribution of normal stars in the very inner galaxy, and especially the properties of an inner bar, if such exists. The integration of these data into new dynamical models is a major topic of activity in the subject today.

The creation and distribution of the chemical elements in the Milky Way is basically understood. The light elements (H, He and some Li) were created in the hot early Universe, while all the others (the "metals") are produced by quiescent or explosive nuclear reactions in stars, with the different chemical elements being created at different, tolerably known, rates. Each stellar generation has enriched the galactic gas with its products and was born with a chemical composition reflecting the evolutionary stage of the Galaxy at that time. All stars less massive than our Sun are still alive today and keep on their surfaces the chemical composition they had at their birth, a fossil record of our Galaxy's history. This record is complemented by the composition of the interstellar medium, which gives the current chemical status of the Galaxy. Despite their relative success, models of the chemical evolution of our Galaxy suffer today from two serious drawbacks: they do not consider kinematics, or the likely dynamical history of the relevant stellar populations; they do not consider the dynamical interaction between the star-forming interstellar medium and the energetic supernovae which are the element creation events. Thus, both small-scale stochastic variations – recently established as real – and large scale systematics remain to be treated adequately, even though these probably contain the most important clues to the important physics. The large scale systematics are especially timely, as the abundance profile of deuterium across the galactic disk, measurable for the first time with the ISO satellite (to be launched later this year), will provide crucial insight into the past history of infall and star formation in the galactic disk.

The development of such enhanced models requires a close interaction between specialists, both observers and theorists, in stellar kinematics, the physics of the interstellar medium, stellar nucleosynthesis and chemical evolution.

Though these many dynamical, structural and chemical evolution questions may seem well-defined and relatively distinct, the answers are intimately interrelated. For instance, galaxies probably accrete their neighbours, so that the place of origin of a star may be far from its present location, dynamical instabilities in disks result in the mixing through phase space of stellar populations, further blurring the relation between a star's present location and its birthplace. Bar instabilities are also likely to cause significant gas transport, and may drive star bursts and possibly nuclear non-thermal phenomena, if a giant black hole lurks in galactic nuclei. The detailed limits on the mass of the Milky Way disk, and the dark matter content of dwarf satellites, are a crucial contribution to the analysis of the new, precise, HI kinematic maps of external galaxies. The chemical evolution, and the relative importance of dark matter to the dynamics, in the dwarf satellites differs substantially from those of larger galaxies. New models and data combining the essential features and physics will isolate the similarities and differences in the evolution of these diverse galaxies, substantially improving our understanding of the diversity of our part of the Universe.

## 2. How Can One Study the Milky Way?

It is widely though erroneously believed that one can see the Milky Way Galaxy. In fact, one's image of the Milky Way depends more on how one looks at it than on what is available to be seen. For reasons which are related to population biology more than to astrophysics, our eyes are optimised to detect the peak energy output from thermal sources with a surface temperature near 6000K. Thus, unless such an object is typical of the entire contents of the Galaxy, there is no reason why we should be able to see by eye a representative part of whatever may be out there. If we had X-ray or UV sensitive eyes we would 'see' only hotter objects, if infrared or microwave eyes only cooler objects.

No single section of the electro-magnetic spectrum provides the 'best' view of the Galaxy. Rather, all views are complementary. However, some views are certainly more representative than are others. The most fundamental must be a view of the entire contents of the Galaxy. Such a view would require access to a universal property of matter, which was independent of the state of that matter. This is provided by gravity, since all matter, by definition, has mass. Mass generates the gravitational potential, which in turns defines the size and the shape of the Galaxy. While the most reliable and comprehensive, such a view is also the hardest to derive. Kinematics and distance data are however the closest approach to such a view which is possible. That is, *an ideal astrophysicist would have astrometric eyes.*

Complementary and relatively readily available views of much of that part of the ordinary baryonic mass whose state has been identified can be provided by the sum of optical and near infrared studies. Much of the mass of the Milky Way is in stars, the more massive of which are visually luminous. Lower mass stars, those objects hiding behind -interstellar extinction, and much of the inter-stellar medium (ISM), are most readily observed in the near infra-red.

The importance of infrared astronomy for study of obscured objects, a property which is of particular significance when studying the central regions of the Galaxy and regions of current or recent star formation, is illustrated in Table 1. This tabulates representative values for the wavelength dependence of extinction, illustrating the relative transparency of interstellar dust at wavelengths just a little longer than those to which our eyes are sensitive.

TABLE ONE

Optical/IR Interstellar Extinction

| Photometric Passband | Wavelength $\mu m$ | Extinction (magnitudes) |
|---|---|---|
| U | 0.36 | 1.56 |
| B | 0.44 | 1.33 |
| V | 0.55 | 1.00 |
| R | 0.64 | 0.78 |
| I | 0.79 | 0.59 |
| J | 1.25 | 0.28 |
| H | 1.65 | 0.17 |
| K | 2.2 | 0.11 |
| L | 3.5 | 0.06 |
| M | 4.8 | 0.02 |
| N | 10 | 0.05 |

Infra-red astronomy provides the closest and greatest complementary match to optical astronomy, while at the same time extending the source temperature range available for study to those lower temperatures at which many known astrophysical sources are to be found, and at which a substantial part of the higher energy radiation is re-emitted.

The net effect of this table is clear: if one has an astrometric satellite which is capable of measuring objects more than a few kpc distant, and with a finite flux sensitivity limit, then one MUST operate in crowded low Galactic latitude fields, in which interstellar extinction is considerable, and one must operate in the near infrared. An order of magnitude gain in sensitivity to astrophysics is attained by counting photons at $2\mu m$ instead of at $0.5\mu m$. The important astrophysical questions are buried as much behind interstellar dust as they are buried behind our ignorance. It is not possible to see a very large fraction of the stars, star formation regions, dynamics, or evolution, in the Galaxy in a survey restricted to low source density and optical passbands.

We emphasise again here that the fields of scientific interest are extremely crowded, and extremely reddened. It is simply not possible to study the astrophysics of the regions of star formation, spiral structure, the inner bulge, the outer disk warp, and so on, through the edge-on spiral galaxy in which we live, without working in crowded and dusty fields. Such is astrophysics. An ability to provide astrophysically important data under such circumstances is a *sine qua non* for an astrophysically interesting study.

## 3. What Precision is Necessary?

In order to quantify the range of astrophysically important questions for which astrometric data are an essential prerequisite, we show in Table 2 a summary of the kinematics, and corresponding proper motions and apparent magnitude limits, expected to be characteristic of known stellar populations. Determination of these kinematic parameters would revolutionise our knowledge and understanding of Galactic structure, formation, and evolution, and of the nature and distribution of matter in the local Universe.

In the Table, the first column identifies the tracer of a specific stellar sub-population, the second the corresponding absolute visual magnitude, the third and fourth the appropriate Galactic coordinates, while the fifth column indicates the minimum distance at which one needs to study such a tracer to achieve fundamental astrophysics. Column six provides an estimate of the velocity dispersion tangential to the line of sight of the tracer sub-population, column seven typical visual extinctions down such a line of sight. The corresponding range of apparent visual magnitudes are presented in columns eight and nine. Column ten indicates the proper motion corresponding to the quoted velocity dispersion, but note that this is not the *mean* proper motion, which is typically smaller by a factor of two. Columns eleven and twelve indicate the expected standard errors of proper motion measurements at the two apparent magnitudes noted in columns eight and nine, assuming the incoherent imaging mode of operation of GAIA.

Thus, one sees from Table 2 that GAIA in incoherent imaging mode can just reach sufficiently faint to achieve nearly all of the desirable astrophysics.

TABLE TWO

### GALACTIC PRIMARY KINEMATIC TRACERS

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tracer | $M_V$ | $\ell^{\circ}$ | $b^{\circ}$ | Dist | $\sigma(U_{tan})$ | $A_V$ | $V_1$ | $V_2$ | $\mu$ | $\sigma_{V1}$ | $\sigma_{V2}$ |
| | mag | (deg.) | (deg.) | kpc | km/s | mag | mag | mag | mas/yr | mas/yr | mas/yr |
| **HALO** | | | | | | | | | | | |
| gM | -1 | – | $< 20$ | 8 | 80 | 2-3 | 15.5 | 16.5 | 2.11 | 0.02 | 0.04 |
| RRLyr, gK | +0.6 | – | $> 20$ | 30 | 80 | 0 | 18.4 | – | 0.56 | 0.10 | – |
| **THICK DISK** | | | | | | | | | | | |
| Miras | -1 | 0 | $< 30$ | 8 | 50 | 2 | 15.5 | – | 1.32 | 0.02 | – |
| RRlyr, gK | +0.6 | 0 | $< 30$ | 8 | 50 | 2 | 17 | – | 1.3 | 0.05 | – |
| Miras | -1 | 180 | $< 30$ | 20 | 30 | 2 | 17.5 | – | 0.32 | 0.07 | – |
| RRlyr, gK | +0.6 | 180 | $< 30$ | 20 | 30 | 2 | 19 | – | 0.3 | 0.12 | – |
| **THIN DISK** | | | | | | | | | | | |
| gM | -1 | 0 | $< 15$ | 8 | 40 | 1–5 | 14.5 | 18.5 | 1.05 | 0.01 | 0.08 |
| gM | -1 | 180 | $< 15$ | 10 | 10 | 1–5 | 15 | 19 | 0.21 | 0.02 | 0.12 |
| **GRAVITY: $\mathcal{K}_{\mathcal{Z}}$** | | | | | | | | | | | |
| dK | +7-8 | 0 | 90 | 2 | $\ll$20 | 0 | 18 | – | $\ll$2 | 0.08 | – |
| **SPIRAL ARMS** | | | | | | | | | | | |
| Cepheids | -4 | – | $< 10$ | 10 | 7 | 3–7 | 14 | 18 | 0.15 | 0.01 | 0.08 |
| BM Supergiants | -5 | – | $< 10$ | 10 | 7 | 3–7 | 13 | 17 | 0.15 | 0.01 | 0.05 |
| **BULGE** | | | | | | | | | | | |
| gM | -1 | 0 | $< 20$ | 8 | 100 | 2-10 | 15.5 | 23.5 | 2.6 | 0.02 | |
| **DISK WARP** | | | | | | | | | | | |
| gM | -1 | 180 | $< 20$ | 20 | $<$10 | 1–5 | 16.5 | 20.5 | $<$0.1 | 0.04 | 0.4 |
| **DISK ASYMM** | | | | | | | | | | | |
| gM | -1 | all | $< 20$ | 20 | $<$10 | 1–5 | 16.5 | 20.5 | $<$0.1 | 0.04 | 0.4 |
| **GLOB CLUSTERS** | | | | | | | | | | | |
| gK | +1 | – | – | 8 | 80 | 0 | 15.5 | – | 2.1 | 0.02 | |

### EXTRAGALACTIC PRIMARY KINEMATIC TRACERS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **SATELLITE GALAXIES: ORBITS** | | | | | | | | | | | |
| gM | -1 | – | – | 100 | 100 | 0 | 19 | – | 0.2 | 0.12 | – |
| **SATELLITE GALAXIES: INTERNAL KINEMATICS** | | | | | | | | | | | |
| gM | -1 | – | – | 100 | $< 10$ | 0 | 19 | – | 0.02 | 0.12 | – |

## Conclusions

Precision astrometry is the most powerful tool potentially available to study the fundamental astrophysics of the formation, evolution and structure of the Milky Way Galaxy, a typical representative of the galaxies which dominate the luminous Universe.

An essential requirement to achieve this potential is an ability to provide accurate astrometric data for large numbers of sources of astrophysical interest. Such sources are, since we live in the Plane of a spiral Galaxy, primarily found in low Galactic latitude fields. Thus, the sources are in crowded fields, and are often considerably obscured by interstellar extinction. Observations in visual wavelengths must therefore reach magnitude limits which require incoherent imaging operation. Probably better would be near infrared operation. Most luminous astrophysical sources which are suitable as kinematic tracers are evolved stars, and so are inherently very red. Combining this with the additional reddening and extinction from interstellar dust, leads to a considerable advantage in sensitivity in the near infrared relative to the optical.

In any case, any experiment which is designed to be able to measure the kinematics of stars across the Galaxy must be able to see across the Galaxy. That presupposes crowded fields, faint limiting magnitudes, and lots of reddening.