HOW DOES THE GALAXY WORK?

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HOW DOES THE GALAXY WORK?

A Galactic Tertulia with Don Cox and Ron Reynolds

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Preface

The international conference *How does the Galaxy work? A galactic tertulia with Don Cox and Ron Reynolds*, was held during the week of 23^{rd} to 27^{th} of June 2003 in the marvelous city of Granada, Spain. This week marked the beginning of one of the hottest summers that we have ever lived, but in contrast, the meeting was one of the coolest events that we can remember! First, it certainly was a first class scientific reunion, with an excellent program, talented speakers, and alive discussions in a friendly atmosphere. Second, the whole event was embedded in the passionate Andalucian way of life, a true tertulia, well seasoned with tasty tapas and perfectly marinated in cool and dry sherry wine. Third, the celebration was framed by some of the most beautiful settings that one can imagine; we enjoyed the magnificent splendor of the Alhambra, the unique Muslim-Jewish-Christian flavor of the Albaicin, and the magical gipsy heartbeat of Sacromonte. Last but not least, all discussions, whether they were during the sessions or at a bar table, were sprinkled with the charm and wit of the two guests of honor: Don Cox and Ron Reynolds. The idea of having a scientific feast to celebrate their 60th birthday in Granada was actually conceived at a bar table in Seville, with plenty of manzanilla at hand, a couple of summers ago. That, perhaps, was the difficult part of the project. The rest was relatively easy to achieve because Don and Ron are not only remarkable astronomers but they are also great human beings. Indeed, we had a very positive response from all parties involved: every person we talked to was enthusiastic about the celebration, and wanted to give their own point of view in this tertulia. By the way, the Spanish word “tertulia" means a friendly get together, or a session, in which all ideas can be aired. It is a moment of song and poetry and wit in conversation.

There were 120 participants, more than 25% of which were women, and a large fraction of them were young scientists. The conference was aimed at revising our conceptions on the present state and evolution of our Galaxy, both at large and small scales. The Milky Way is a massive spiral and has many structural features that, while interesting on their own, interactively play significant roles in continuously reshaping it and determining its fate: a central black hole, an internal bar structure, magnetic fields, molecular and atomic gas, giant star formation regions, stellar population gradients and aggregations, and a rotation curve indicative of a dominant dark matter component. The ultimate task one can envision is to construct a self-consistent picture of galaxy evolution, but the actual and more humble goal in this meeting was to evaluate our understanding about the role of the thick interstellar gaseous disk in the context of large-scale galactic processes.

Ron Reynolds and associates have mapped and derived the details of the thick layer of ionized gas in our Galaxy. Their results are far reaching and have important consequences about the properties of the general interstellar medium because this gas, which is excited by stellar energy, is not only following the gravitational field of the Galaxy, but perhaps is also responding to the general magnetic field. From the theoretical point of view, on the other side, Don Cox and collaborators have pioneered investigations into the large-scale influences of supernovae on the structure and dynamics of the interstellar medium, and shown that the thick disk can be in magnetohydrodynamic equilibrium, in a time-averaged sense, as long as it is supported by magnetic fields, cosmic rays, and turbulent pressure. Thick gaseous disks have now been observed in many edge-on galaxies, and a good number of issues relating them with our own thick disk have been reviewed in this conference. This is well reflected in the present book, that contains the invited talks and most of the contributed papers. By the way, Steve Shore and Bruce Elmegreen were unable to come to Granada during the festivities, but they joined us in the celebration with a very touching personal letter (Bruce) and a very fine paper on the history of the Milky Way research (Steve). We thank both of them for their nice contributions, which are also included in this book.

We warmly thank the rest of the Scientific Organizing Committee, Rainer Beck, Bob Benjamin, Yo-Hua Chu, Ralf Dettmar, Bruce Elmegreen, Carl Heiles, Katia Ferrière, Isabelle Grenier, Marco Martos, Casiana Muñoz, John Raymond, Wilt Sanders, Steve Shore, and Chema Torrelles, for their help in preparing the scientific program. We are also indebted to our Local Organizing Committee, Antxón Alberdi, Antonio Delgado, Mariano Domenicone, Martín Guerrero, Paco Rendón, Rafael Rodrigo, Pepe Ruedas, and Pepe Vílchez; they were very efficient in solving all the details of this conference. Very special thanks go to Susana Gómez and Fina Molina from the Instituto de Astrofísica de Andalucía, and to our energetic young LOC team, María Aldaya, Beni Cantero, Daniel Espada–Fernández, Silbia López–Lacalle, David Martín–Gordón, Tony Mee, and Daniel Reverte-Payá, for making this a trouble-free event.

Finally, we thank the Ministerio de Ciencia y Tecnología of Spain, CSIC, Junta de Andalucia, Diputación de Granada, Ayuntamiento de Granada, Instituto de Astrofísica de Andalucía, Instituto de Astronomía – UNAM (México), and Sociedad Española de Astronomía (SEA) for their generous financial support which made this conference possible.

The Editors

Spring of 2004, México City and Granada

Bruce's letter

Dear Don and Ron,

I am sorry I cannot be with you to celebrate on this important occasion but age has advanced on our family too as my son is just this week graduating from High School.

I remember well the time of my thesis when I marveled at Ron's early H-alpha survey that he did with my old physics teacher, Frank Scherb. And how at the same time Don proposed that hot gas was everywhere in space. I was a young graduate student who had just escaped from the revolutionary cauldron at UW and landed in the midst of peaceful serenity at Princeton. The news from Wisconsin was as radical as ever: ionization everywhere, hot gas everywhere. You turned the prairie ISM into a raging brush fire. You started the revolution that now sees explosions and turbulence and fractals and disequilibrium instead of pressure balance and slow contractions in those grinning pumpkins that were once standard clouds. You gave me something fun and dynamic and controversial to study for all of these years.

I celebrate your exciting discoveries and drink a toast to beautiful Granada.

Bruce Elmegreen


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THE MILKY WAY: FOUR CENTURIES OF DISCOVERY OF THE GALAXY

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Abstract This general introduction is intended to place the present meeting in a broader historical context, highlighting some of the critical junctions in our understanding of the small and large scale structure and evolution of the Galaxy.

1. Introductory Remarks

The first Granada meeting – ten years ago – on the *Formation of the Milky Way*[1] occurred at a critical moment in the development of Galactic astrophysics. The Hipparcos catalog had not yet been released but the satellite had successfully completed its primary mission. Several large scale surveys for neutral atomic and molecular gas had been completed in the previous decade. The COBE data had been released for cosmology but much remained to be done for Galactic structure and ISO was still in the future. The neither the 2MASS the SDSS had begin, microlensing surveys were underway but still far from finished, and HST was still in its early (difficult) years of operation. How the world's changed: we have now almost a surfeit of data and it's the purpose of this short note (and the "vice of age") to put some of these more recent advances of our understanding in a wider context.[2] It's often too easy to think any area of astrophysics was "born yesterday". Recognizing the Milky Way as one of a vast number of stellar systems was one product of the last century, and the birth of modern observational cosmology. But we have more recently come to understand that many clustered systems, on size scales ranging from hundreds of kpc to many Mpc, are not completely relaxed (i.e. *virialized*) and therefore are subject to both dynamical and population modification over time. Here we

[1]Alfaro, E. J. & Delgado, A. J. eds. 1995, *The Formation of the Milky Way* (Cambridge: Cambridge Univ. Press); hereafter referred to as "G1".

[2]At the outset, the reader should note that this essay is one person's musings in the hope of stimulating others'. I don't intend to be comprehensive in reviewing the literature and references are for perspective and as pointers to further work.

E.J. Alfaro et al. (eds.), How Does the Galaxy Work?, 1–14.

see one of the major shifts in the picture from the G1 meeting: the early view of an isolated unique system has been replaced by one far richer in phenomena but also far less simple when attempting to explicate its formation and evolution.

In the broadest outline, there have been several stages in the "discovery" of the Milky Way: understanding the gross structure and size but as an essentially one component (stellar) object (17th and 18th century), seeing it as a complex multicomponent dynamical system (19th and first half of the 20th century), then recognizing that it is just one of a vast array of systems (1st half of the 20th century), and finally seeing it as an evolving dynamical system not in isolation (2nd half of the 20th century and into this century).

2. Prehistory

Galileo first described the Milky Way as a resolved (and resolvable) stellar system in 1610, in his *Siderius Nuncius*, [3] reporting the discovery of a seemingly endless sequence progressively fainter stars in every field he examined. The *visible* stars were just the tip of the brightness distribution. He also noted a clustering hierarchy (for instance, when viewing the Pleiades) although this was described only in very qualitative terms. It's interesting to realize that when applied to the Galaxy, Galileo's use of the telescope actually resembled Leeuwenhoek's and Hooke's microscopy: the smallest, faintest scale was the undiscovered territory while the large scale structure, the disk, was apparent.[4] Nearly a century later, the vastness of the panorama presented by these observations was considered by Newton who, in the propositions of the third book and General Scholium of the second edition of the *Principia* (1712/13), treated the questions of dynamics and stability of the larger scale amid his most explicit theological musings. Halley was quick to point out the contradictions between the stability and the darkness[5] opening the door to a dynamical evolving cosmos through the action of universal gravitation – in other words, the possibility of structure formation on all scales from stars to large systems of stars and ultimately to the largest clusters.

[3]For a history of the early work on the Galaxy, see Jaki, S. L. 1972, *The Milky Way: An Elusive Road for Science* (NY: Science History Publ.)

[4]Galileo's Galactic discoveries were actually more astonishing to his contemporaries than those in the Solar system. For *this* reason he was hailed as the "new Columbus". You see this, for instance, in Huygens and Fontenelle, the prospect of numberless new worlds.

[5]1720, Phil Trans. Roy. Soc., 31, 22. Later, following Bondi (1960, *Cosmology* (Cambridge: Cambridge Univ. Press)), this would be called "Olbers' Paradox" and the dark sky question would become increasingly important for broader cosmological questions beginning in the 19th century.

3. The Milky Way from Inside

Structure: Galactic structure modeling – the stellar component – began about 200 years ago with the series of papers by William Herschel on "The Construction of the Heavens" (beginning with his paper of 1785, Phil Trans. Roy. Soc., 75, 213)[6] His basic assumptions differ in some significant ways from those employed in models presented at this and the previous Granada meeting, but they illustrate the enormous progress we have made while contemplating the universe from a speck. First, Herschel assumed a spatially and temporally invariant luminosity function for the stars, essentially a δ-function for this distribution being unable to deal with what he knew from clusters to be a broader range of intrinsic brightness. Assuming that the observed distribution (morphology) is identical to structure, and being ignorant of other components than stellar affecting his statistical inferences, he obtained a strongly nonsymmetric model that couldn't possibly accord with any dynamics; it placed the Sun far from the center of luminosity (and mass). Following the discovery of binary stars (from proper motion and statistical excess of close pairs and associations), it was obvious that the stars have an spread in intrinsic luminosity, but without clusters and the determination of their luminosity functions and those of the field stars (work begun in the 1920s).[7] there was no way to use star counts alone to properly model the observed projected surface brightness. The Schmidt telescope, invented in the 1930s, provided the necessary tool for large scale spectroscopic and imaging surveys of the Galaxy, used especially by Nassau and McCuskey (e.g. Nassau,J. J. 1945, ApJ, 101, 275) and later with the much larger Palomar, ESO, and AAO Schmidt telescopes using photographic multifilter imaging and objective prisms (although this technique was introduced in the 19th century used by Secchi and the Harvard groups for classification). Now the use of large mosaic CCDs, have finally provided the necessary photometrically calibrated data sets and Galactic structure modeling is a ",mature industry".

The Gas: The gaseous component in the Milky Way was invoked by Laplace in his nebular model for the origin of the Sun and the solar system; it was also used at around the same time as a possible solution to the dark sky problem. Nebular objects were cataloged by many observers, and numerous such structures were described by visual observers beginning with William, Caroline,

[6]see Hoskin, M. A. 1964, *William Herschel and the Construction of the Heavens* (NY: Norton); Hoskin, M. A. 1982, *Stellar Astronomy: Historical Studies* (Chalfont: Science History Publ.). For more general discussions of the historical development, see Whitney, C. A. 1971, *The Discovery of Our Galaxy* (NY: Knopf); Struve, O. and Zebergs, V. 1962, *Astronomy of the 20th Century* (NY: Macmillan); Berendzen, R., Hart, R., and Seeley, D. 1976, *Man Discovers the Galaxies* (NY: Science History Press).

[7]The Malmquist bias, now fundamental to understanding luminosity surveys, was introduced as a statistical correction for the stellar luminosity function.

and John Herschel at the start of the century[8], many had resolved into stars and there was some doubt about whether gaseous objects existed at all, even following the work under William Parsons (Third Earl of Rosse) (e.g. 1860-62, Proc. Roy. Soc., 11, 375). Only spectroscopic observations finally closed the debate on the existence of a diffuse phase to the Galaxy. The first spectrum of a gaseous nebulae was obtained for NGC 6543, in Draco, by William Huggins (1862, Phil. Trans. Roy. Soc., 154, 437). Unable to identify the lines with known laboratory counterparts, he argued that the two strong emission lines he observed constituted the discovery of a new cosmic element, *nebulium.* In fact, this observation simply demonstrated that highly ionized gas exists in the vicinity of stars, not of the *interstellar medium.* Understanding the origin of this material, and its connection with star formation, came later from the discovery of of the warm medium through observations of stationary Ca II lines in the spectra of several binary stars for which spectroscopic orbits showed the bound motion of the stellar components by Vogel, Hartmann, and Pickering at the end of the 19th century (Clerke, A. 1902, *Problems in Astrophysics* London: Nelson). We now know this too is just a piece of the picture. There are many phases in the diffuse gas and the temperatures range from tens to millions of degrees. Eddington (1927, *The Internal Constitution of the Stars* (Cambridge: Cambridge Univ. Press) explained the array of ionization states observed as a NLTE effect in a very low density medium, forbidden lines became fundamental tools through the work of Aller and others in the 1940s, and the hottest phase of the medium was predicted by Spitzer for the Galactic corona before 1950. We know the physical reason for this bizarre state of the medium is because of its low density and long dynamical timescales relative to the thermal timescale: regions can be wildly out of thermal equilibrium over comparatively short distances. Also, there are many sources of heating – supernovae, expanding H II regions, photodissociation and photoionization regions, cosmic rays, and local magnetic reconnection and MHD turbulence.

The first photographic atlases of the plane by Barnard, and images of specific regions by Ritchie, showed filamentary emission and absorption regions scattered throughout the Galaxy. The existence of multiple clouds along many lines of sight, along with their different abundances and optical depths, requires spectroscopy but by the middle of the 20th century this was already apparent. There were even some visual discoveries in the 19th century of large, diffuse structures (in particular, the Barnard Loop in Orion), but these were too low surface brightness to be studied with then-available spectroscopes; however, these observations dynamics couldn't be assessed from such observations but that became possible with the invention of imaging interferometric spectroscopy by

[8]Messier too had described many such objects but less systematically and without any particular physical purposes, as Herschel later implied in his series.

Fabry and Perot (see e.g. Buisson, H., Fabry, C.,& Bourget, H. 1914, ApJ, 40, 241 and references therein) who made considerable progress for specific, more compact regions early in the 20th century,[9] and after the 1940s the use of narrow filters at Hα, [O III], [N II], and Hβ along with more sensitive photographic plates (e.g. the Palomar sky survey), image tube and vidicon detectors extended the identifications. For extragalactic systems this also proved quite simple, especially when theoretical work by Raymond, Cox and their collaborators showed specific plasma diagnostics that can distinguish between supernova remnants (e.g. using [S II]) and H II regions. Surveys of the Magellanic Clouds and the Local Group galaxies (especially M 31 and M 33) were essential in developing the picture of the Milky Way since, having the whole galaxy available for study without the ambiguities of distance and location, produced intrinsic luminosity distributions for the various nebular environments. The complete Galactic survey of such regions was not achieved until the work of Reynolds and his collaborators, the discovery of the Hα emitting Reynolds layer of ionized gas.

Here too imaging CCDs, mosaics and high S/N spectrophotometric imaging have vastly extended our knowledge of these structures, also combined with the development of radio and millimeter imaging interferometers. It is now possible to panchromatically view the Galaxy with an almost uniform minimum resolution of a few arcseconds, comparable to the photographic surveys.

Magnetic Fields: I'll be brief here. The magnetic field was the last component of the Galaxy to be discovered. Radio emission from the plane was accidentally detected by Jansky (1933-1935) and mapped by Reber (1944, ApJ, 100, 279). However, its connection with magnetic fields and cosmic rays wasn't immediately appreciated and it took about a decade to realize how it can be explained by synchrotron emission.[10] Combined with the discovery of optical interstellar polarization, and now using pulsar dispersion measures and extragalactic Faraday rotation, the large scale structure is emerging. Direct Zeeman measurements are now almost routine and as sensitivities in the millimeter and centimeter improve more of the large scale, diffuse field will become accessible (for instance, in the Galactic center).

Dynamics: Stellar distances were first secured with the determination of the parallax to 16 Cyg B by Bessel in 1848, but progress was severely hampered for nearly a century because of the paucity of nearby bright stars and the fundamental resolution limits of the early observations. It should be noted that, in his pioneering structural studies, Herschel didn't ignore kinematics, having

[9] Buisson, H., Fabry, C., and Bourget, H. 1914, ApJ, 40, 241 and references therein)

[10] Also the Fermi mechanism (Fermi, E. 1949, Phys. Rev., 75, 1169) required also that the magnetic field couple to the dynamics of the gas. And it's also important to note the first stability discussions related to the coupling of the gas and the Galactic magnetic field by Chandrasekhar, S. & Fermi, E. 1953, ApJ, 118, 113.

also determined the apex of solar motion (1783, Phil. Trans. Roy. Soc., 73, 247). These results remained separated in his, and others' work for nearly a century since the temporal baselines were insufficient. Before the 1920's, little progress could be made in the study of space motions (again, in part, because of the angular resolution limits and the lack of stable emulsions for astrometry). Space velocity systematics were characterized by K. Schwarzschild (1912, Astr. Nach., 190, 361, for instance) using an anisotropic Gaussian distribution, based on proper motion data, providing the first dynamical hint that the Galaxy isn't completely relaxed, and the crucial proper motion observations by Kapteyn indicating a "special place" for the Sun (see Merritt, D. 1999, PASP, 111, 129 for a modern review of the velocity distribution).

These astrometric data also established a fundamental feature of the stellar populations, the enormous range of luminosities *and* the correct interpretation of what, by 1913, would become the standard tool for stellar astrophysics: the Hertzsprung-Russel (HR) diagram. Although Maury had described a distinct, parallel spectral sequence of narrow lined stars to those of what we now call the main sequence (her class *c* objects), it fell to Hertzsprung to show that these stars are actually at systematically larger distance and, therefore, at higher luminosity.

Spectral classification was useful for understanding the stellar population itself but, following the introduction of specific luminosity taxonomic criteria by Morgan, Keenan, and Kellman (MKK) (1943), provided a new tool for the exploration of the Milky Way. Spectral morphology is distance and reddening independent, except for the interstellar line contributions that are easily distinguished and excluded. Thus, an independent determination of the distribution of the sites of star formation is possible even without the benefit of kinematic information from the rotation curve; this is essential for work beyond the solar circle, particularly for determining the rotation curve and, through it, the halo dark matter distribution. Yet again, the search draws its inspiration from external galaxies, for which the signature of such halos is unambiguous in the stars *and* gas. Even before the first H I maps (Oort, J. H., Kerr, F. J.& Westerhout, G. 1958, MNRAS, 118, 379), spiral structure was suspected from the OB star distributions. Now the stellar arms are more certain now, of course, because we also have the gas to serve as a density and velocity tracer of the large scale flow. But in the 1950s, the first attempts to find this structure were strikingly successful. Reddening – and extinction – for distant stars in the plane hampered the study of both structure and history of star formation in the disk. These are related, we now know, but it wasn't obvious at the start that without a clear idea of the intrinsic colors or a complete knowledge of the intrinsic luminosity function, it is impossible to determine the details of the structure and age of stellar systems.

The large scale motions were kinematically modeled by Oort, just 80 years ago, whose successful Copernican-Galilean transformation to an orbiting reference frame finally removed the contradiction between the symmetry required for a self-gravitating system and the apparent special location of the local standard of rest (LSR). By displacing the center of symmetry from the LSR, mass modeling became possible with the additional constraint that comes from the velocity at the solar circle. This isn't a trivial point: interstellar obscuration toward the Galactic center and bulge makes it impossible to unambiguously determine structure without substantial assumptions regarding the overall symmetry of the mass. Before the last two decades – that is, before the big picture provided by mid-IR surveys by IRAS, COBE, and now 2MASS – no overall view was available of Galactic structure in three dimensions.

What we now have is a structurally complex, but essentially consistent, picture. The central region resembles a peanut system, the sort of structure seen in barred spirals. The plane is warped. Large scale abundance gradients exist, as we also find in most disk galaxies. The catalog of members of the Local Group dwarf population is still growing, including in-plane surveys for obscured members.

The Milky Way from Outside

From within, given the limitations imposed by (then unknown) interstellar reddening, everything known about the Galaxy was essentially local before the 1920's. This fundamentally changed after, what I'll suggest, were two pivotal steps: realizing that the Galaxy is simply one of many massive, separate stellar system – being able to use the label "extragalactic" – and Hubble's study of M 31 as a spiral galaxy (Shapley, Curtis, Hubble). The story of the "Great Debate" between Shapley and Curtis is too well known to bear repeating. But it is important to note that much of our view of the Milky Way follows from the methods used by the protagonists to study the structure: the recognition that galaxies are external stellar systems fundamentally changed the perspective.

If you will pardon the use of the word, consider the epistemological value of this discovery. Before seeing the Milky Way as *a* galaxy – instead of *the* Galaxy – one wouldn't think to look for globular clusters; after all, if the spirals are just forming low mass systems, they couldn't possibly have their own cluster systems. Observers looked for variable objects – novae, Cepheid and RR Lyr variables, eclipsing binary stars and the like, but the *luminosities* of these objects were not appreciated; you see this in the Shapley-Curtis debate with respect to S And. And without knowing the distances to other galaxies, or at least of their existence, *supernovae* and, now, *hypernovae* could not have been distinguished without spectroscopy (which was then too limited in sensitivity).

Even our view of the morphology of the Galaxy has come from outside: the debate about the *Hubble class* of the spiral (following Hubble's morphological system based not only on the winding of the arms but also the bulge to disk ratio). Current models for the halo adopt a de Vaucouleurs "1/4" law, but recall that this came from analyses of elliptical galaxies. The signatures of bars, bulges, and warps came first to light in extragalactic systems. Now these are used to interpret observations of the Milky Way. Chimneys, fountains, bubbles and superbubbles, all were first seen in external galaxies. Astronomers have never been accused of lacking imagination or ingenuity, so this short list should highlight just how difficult it really is to unravel these components from only *in situ* measurements. Guided, however, by many insights from the Local Group, enormous progress could be made quickly and, by the 1960's, many of the basic ingredients of the models discussed at this meeting were in place. But there's also a dividend from this extragalactic view: we also know what to look for in *our* system to explain the phenomena in others, for instance for Dark Matter (see below).[11]

With the Hubble law, bootstrap calibrations of the distance scale, and studies of large scale structure of the luminous matter (beginning with Shapley's suggestion of the local supercluster and continuing through the studies of Zwicky and Abell), new phenomena could be distinguished *within* the Galaxy by analogy with external examples. Consider that without knowing about external systems, clustering, Mpc scale dark matter, and large scale structure would never have been sought (although there was evidence of a dark component to the disk from local dynamical studies before the virial mass deficits were ascertained in clusters of galaxies). Statistical methods, originating from and extending the Herschel methodology, were used for nearly a century to map the large scale structure. One should recall that binary *galaxies* (e.g. Page) and *galaxy* clusters (e.g. Shapley, Zwicky, and the Lick group) were first found in the 1930's using the same statistical arguments that revealed binary *stars* and *star* clusters a century earlier. The same can be said for galaxy cluster surveys.[12]

Spiral structure is ubiquitously observed in disk galaxies, and was therefore expected to exist in the Milky Way even in the absence of excitation mechanisms (although magnetic fields were implicated early in the discussion). The critical information was already provided by dynamical mass models for the system and independent methods of determining the distance to the Galactic center. The

[11]The first instance of Galactic "dark matter" may be the *Zone of Avoidance* described by Hubble (1936, *The Realm of the Nebulae* (New Haven: Yale Univ. Press)). This region, understood analogously to edge-on spirals and studied in tandem, was delineated by the surface distribution of extragalactic objects, more detailed mapping now reveals even the fine structures observed in the H I and synchrotron maps.

[12]See, for instance, the pioneering work of Neyman, J., Scott, E., & Shane, C. D. 1954, ApJS, 1, 269. See also the third (1956) *Berkeley Symposium on Mathematical Statistics and Probability*, which served as a forum for assembling many of the principals in this work.

mechanism was provided by *density wave theory* in the 1960s, and despite nearly 40 years this is still a work in progress. The basic theoretical idea is simply that the self-gravitating disk is unstable to spiral modes that can be driven by large scale nonaxisymmetric structures and/or time dependent perturbations (such as tidal interactions, see below). We also now know that the Milky Way has a dynamical structure within the inner 5 kpc that has a pattern speed somewhat lower than the spiral arms, analogous to the structure observed in barred spiral galaxies. And the search for interactions with other galaxies in the Local Group was spurred by the pioneering work on extragalactic systems by, for instance, Arp, Ambartsumian, Vorontsov-Vel'Yaminov, and E. and G. Burbidge.

4. Star Formation

How to form stars was only an issue once stellar ages could be assessed from some fundamental theory. This also required thermodynamics, even without nuclear processing providing the requisite fuel.

A minimum lifetime for a luminous self-gravitating mass – a star – comes from the Kelvin-Helmholtz (thermal) timescale. The only constraints are hydrostatic equilibrium and an initial energy budget from the gravitational binding energy. However incorrect this is for any main sequence model, it does lead immediately to the realization that stars must form over the long timescale since the cooling time can be obtained at every luminosity. Hence, one already knew as soon as the HR diagram was constructed that star formation is a continuing process in the Galaxy: OB stars are intrinsically more luminous than G and K stars.

To determine the mass function, to even recognize its existence, required a basic theory of main sequence evolution and some means to trace stars back to their origins in a color-magnitude diagram. The luminosity function is trivial to obtain, in fact these had been accumulated from even crude photographic data before 1940, but few clusters were observable with such insensitive means, and before proper motion and radial velocity measurements could ascertain membership, to extend the interpretation to a cluster mass distribution function. Since the pioneering work of Salpeter (1955, ApJ, 121, 161), this function has taken on the character of a universal distribution, the *initial mass function*. Its precise form is still a matter of debate (Scalo, J. 1986, 1986, FCPh, 11, 1; e.g. Kroupa, P. & Boily, C. M. 2002, MNRAS, 336, 1188) but the methodological underpinnings haven't).

Cluster simulations have become routine through the combined use of atmospheric models and systematic isochrones. During G1, the *Hipparcos* cluster and association data was eagerly awaited; this meeting anticipates the launch of GAIA, the next generation survey. What has emerged since G1 is essentially a confirmation of the fundamental picture of stellar evolution on and near the