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PROBING STRUCTURE AND POPULATIONS OF OUR GALAXY USING THE KINEMATICS OF OLD STARS. I

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RESUMEN

Si se parte del principio que la Vía Láctea constituye un buen prototipo de otras galaxias, ésta ofrece una oportunidad sin par en la realización de estudios detallados de la estructura Galáctica. A diferencia de otras galaxias, en la nuestra es posible estudiar la cinemática de las estrellas que la constituyen. La primera parte de este trabajo está centrada en el análisis de la cinemática. La segunda parte está incluida en este mismo volumen.

ABSTRACT

Assuming our Galaxy to be roughly prototypical of other galaxies, it offers us a unique opportunity for in depth studies of galactic structure. Unlike any other galaxy, it allows us to study the full kinematics of its stars. Here, a basic overview of the methods and requirements involved in the study are given. This first part deals with the analysis of the current kinematics. The second part can be found in this volume.

Key Words: **ASTROMETRY — GALAXY: KINEMATICS AND DYNAMICS — GALAXY: STRUCTURE — STARS: HORIZONTAL BRANCH — STARS: KINEMATICS**

1. INTRODUCTION

Even after more than two centuries of Galactic research, there are still a number of open issues. One is the formation of the Galaxy, and especially its halo. Several theories have been formulated to describe its formation process. The most famous ones are the protocloud collapse scenario by Eggen et al. (1962, ELS) and the scenario of a hierarchical build up of the halo by protogalactic fragments (Searle & Zinn, 1978, SZ). Connected to this, there are questions concerning the outer extent of the halo and possible substructures within the halo and the thick disk. Due to their elusiveness, the inner parts of the Galaxy, most notably the Galactic bulge and a possible bar, are still under intense study and debate. So is the content of dark matter in the Milky Way, since it became clear that a lot of the mass of our Galaxy and other galaxies cannot be explained by visible matter alone.

The Milky Way is the most accessible galactic system, allowing an insight which cannot be gained from the study of other galaxies. It allows us unique access to two important entities: intrinsically faint stars and the full kinematics of stars. However, it presents us with some complications; these are caused by the solar system's position well inside the Galaxy's disk, with the inner bulge region being mostly obscured by dust, and the spiral arms being difficult to trace due to geometric reasons. Therefore, many aspects we assume to know about our own Galaxy originally come from observing other galaxies. However, our Galaxy does allow us unique access to intrinsically faint stars, the full kinematics of stars, and also a clear separation of different stellar populations.

Studying the stellar component and its kinematics can at least partly resolve some of these open issues. I will describe some of the methods involved, focusing on the study of stellar kinematics. Possible tracer objects will be discussed, as well as involved quantities and also probable selection effects and caveats. Unfortunately, this can only be a rough overview and will leave many questions unanswered. More complete information about kinematics or Galactic structure/evolution can be found in one of the following sources: Binney & Tremaine (1987), Binney & Merrifield (1998) and Majewski (1993). This paper explains the principles of object selection, data collection and analysis of current kinematics. The second part (also in this volume) deals with analysis of orbits and finally gives some examples

2. KINEMATIC ANALYSIS STEP BY STEP

2.1. *Tracer stars*

Principally, almost every type of star is a possible candidate tracer object for studies of kinematics or spatial distribution. However, the tracers should

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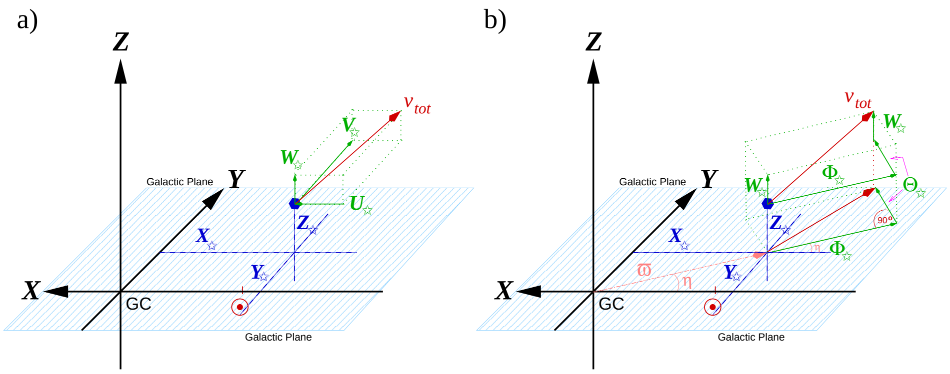

Fig. 1. The 3 dimensional Galactic coordinate systems. The left panel shows the Galactic Euclidian coordinate system (GECS), and the right panel the Galactic Cylindrical coordinate system (GCCS).

have a few important qualities; they should be as luminous and numerous as possible, they should ideally be easily and unambiguously classifiable, their physical parameters (e.g. surface gravity, temperature, abundances, radial velocity, etc.) should be well defined and accurately measurable. Often the choice of a suitable tracer also depends on the part of the Galaxy that is being studied. Most object types do not exhibit all of these qualities, but some object types have shown to be especially valuable tracers. These are stars of the horizontal branch (especially, HBA, sdB and RR Lyrae stars), red giants, white dwarfs and globular clusters.

Here mainly studies involving HB stars and WDs are presented. Blue HB stars and WDs have one big advantage - they are blue objects. Far from the Galactic plane, there are almost no other hot stellar objects, so that identification is straightforward, RR Lyraes are easily found due to their variability. White dwarfs are very numerous. Unfortunately, most of them also have drawbacks. For example, WDs are intrinsically very faint, so that even relatively nearby specimens are rather elusive. The spatial range of a study of a sample of white dwarfs is very limited. Moreover, especially the very interesting cool WDs do not show many lines (or any at all) in their spectra, so that derivation of e.g. radial velocities is difficult, if not impossible. Some BHB stars can be confused with B-main sequence stars close to the disk (for this reason, HBB stars have hitherto been little studied), and HB stars hotter than about 10000 K (including sdB stars), have abundances heavily altered due to diffusion and levitation processes in their inert atmospheres. RR-Lyraes change their brightness and spectra due to their pulsations, making e.g. the derivation of distances more difficult. As can be clearly seen each of these tracers have their virtues and also vices.

The data used for the examples in this paper come from publications made over recent years by our group. These include de Boer et al. (1997), Altmann & de Boer (2000), Altmann et al. (2004), Kaempf et al. (2005), Pauli et al. (2003,2005) and Maintz & de Boer (2005). For more detailed information, the reader is referred to these studies.

2.2. *Obtaining the required quantities*

Before starting to think about actual measurements, we need to set up an ensemble of objects belonging to the object type we have selected to use. Rather than starting from scratch, one should consult literature first. Especially for blue objects away from the plane, there exist several catalogues primarily compiled to survey QSOs, AGNs and other blue extragalactic objects, such as the Palomar Green survey (Green et al. 1986) or the two surveys conducted in Hamburg (the Hamburg-QSO survey and the Hamburg-ESO survey). For variable objects, there are sources like the General Catalogue of variable stars. Last but not least, catalogues like the Hipparcos (ESA, 1997) or Tycho 2 (Høg & Mackarov 2000) catalogues also allow the assembly of samples, with the advantage that some of the required data is already included. However, as with all sources, the limitations of these catalogues must also be taken into account, e.g. the Hipparcos catalogue is not complete at magnitudes fainter than 7.3. Many sources lack objects close to the Galactic plane or nearby and hence bright objects.

Once a sample of candidate objects is assembled, we need to collect distances, proper motions and radial velocities. As far as possible, we would take data from the literature - thus sparing the necessity to observe and derive our own data. In some cases, distances can be derived directly through trigonometric parallaxes (e.g. taken from Hipparcos). However, the objects are too far away in most cases so that more indirect means must be invoked. Most of the distances of our sdB stars were derived by using the method of flux conservation (see e.g. Heber 1986). For the sample of HBA stars of Altmann & de Boer (2000), we used a method to average out the trigonometric parallaxes (see that work, but also Gratton 1998; and Popowski & Gould 1999). For stars of a well defines luminosity, such as HB stars (including RR Lyr), a standard absolute magnitude can be used. Radial velocities can also be obtained through sources in literature (Evans 1967, or Barbier-Brossat 1989) or they have to be derived using spectroscopy. For proper motions more and more reliable sources are coming up. Not only Hipparcos and Tycho 2, but also the whole sky catalogues of USNO (Monet et al. 2003), UCAC (Zacharias et al. 1997) and the S/NPM (Platais et al. 1998, Hanson 1995). For many studies, these are accurate enough, but for far away objects, such as globular clusters[2], own proper motions must be obtained using old -mostly photographic - material and newer data, which can be either CCD or photographic plates.

2.3. *Analysing kinematics*

Often the position and velocity of a star in the Galaxy is given by the Galactic Cartesian system of spatial (XYZ) and velocity coordinates (UVW) shown in Fig. 1, left panel. This system places its origin at the Galactic centre and the Sun at (X=−8.5 kpc, Y=0.0 kpc, Z= a few pc). The velocity vectors point in direction according to the spatial vectors ($U=\dot{X}$, $V = \dot{Y}$, $W = \dot{Z}$). The velocity coordinates of the local standard of rest (LSR) are (0 km s^{-1},220 km s^{-1},0 km s^{-1}). Note that sometimes the origin of the velocity coordinate system is put at (0,0,0). For samples of local stars, these velocities can already provide valuable information. For example, they can tell whether the stars in the sample are generally moving with Galactic rotation or not. The dispersion of these velocities gives information about the spread in kinematics. Stars belonging to the disk will follow its rotation and the spread in the velocities will be small. On the other hand, having a spheroid, non- or little-rotating population, such as the Galactic halo, will result in small values for the average velocity in direction of disk rotation (near the Sun represented by V) and large velocity dispersions, since these stars move in all directions. However, in case a sample is more than very local, the

[2]Many GCs already have good measured proper motions

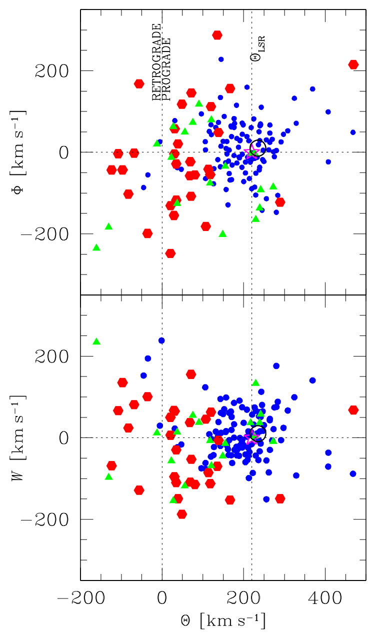

Fig. 2. Example for a Bottlinger diagram. The different symbols depict different types of stars (Large hexagons represent HBA stars, triangles HBB stars, and small hexagons sdB stars - the LSR is shown by an open star and the Sun by a circle). It is evident that the objects of these types have different kinematics; They mostly belong to different populations. The HBAs are mostly at small circular velocities and show a wide spread in all velocity components. Not taking part in Galactic rotation, they are typical Halo stars. The sdBs, on the other hand, cluster at values of Θ only a bit less of that of the LSR - most of these are members of thin and thick disk - however a halo component exists. The HBBs seem to be more or less evenly spread between halo and disk.

values for averages and dispersions will be misleading since away from the axis Galactic centre - Sun, the direction of Galactic rotation is a linear combination of U and V. Therefore, using a slightly different coordinate system for the velocities is more adequate. It is a cylindrical system (see Fig. 1, right panel), where U and V are replaced by the circular or orbital velocity Θ and the radial planar velocity Φ (also known as Π). The vertical component W stays unchanged. At the position of the Sun, the LSR's values are ($\Phi = 0$, $\Theta = 0$, $W = 0$).

Another important related quantity is the angular momentum per unit mass, I (also known as J or L, $\vec{I} = \vec{r} \times \vec{p}$), especially its component in Z direction, I_z. This is a conserved quantity, i.e. better suited to characterise a single object's kinematics than Θ, which changes during its orbit (e.g., the orbital velocity of the Sun by 34 km s^{-1}during its orbit). On the other hand, given the flatness of the Galaxy's rota-

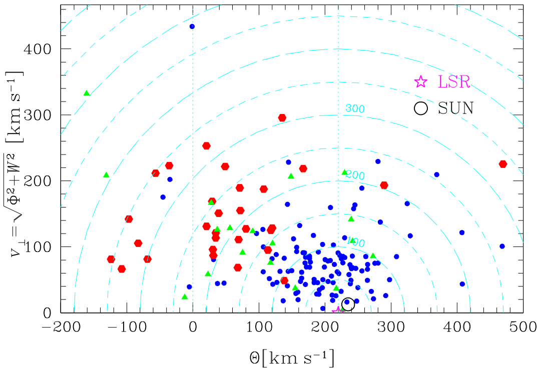

Fig. 3. Example for a Toomre diagram. The symbols depict different types of stars (see Fig. 2). This diagram plots the orbital velocity (Θ) against the velocity perpendicular to Galactic rotation ($v_{\perp}$). It immediately shows the deviations from a circular orbit. The circles denote the total peculiar velocity ($v_{\rm pec}$). Stars having a large peculiar velocity do not take part in Galactic rotation. They, therefore, belong to the spherical component (halo). Those with a small overall deviation are disk stars; a very small $v_{\rm pec}$ means that an object belongs to the thin disk, somewhat larger values put a given object into the thick disk. Comparison with Fig. 2 shows the same evidence of population membership as the Bottlinger diagrams.

tion curve near the Sun, I_z is more dependant on the mean distance to the Galactic centre than Θ. Now, these quantities are the tools we use to disseminate the kinematical properties of our sample stars. In order to facilitate this task, we employ graphical tools. Even a simple histogram over one of the velocities can give a lot of insight regarding the properties of a starsample. A histogram over, e.g., θ immediately shows whether the objects are following Galactic rotation or not and their velocity spread. Even the presence of more than one kinematic group may show up on such a histogram. Other often used tools are the Bottlinger and Toomre diagrams shown in Fig. 2 and 3. The former (actually there are two Bottlinger diagrams) gives information about the average Θ and Φ resp. W and its spread, while the Toomre diagram shows the total velocity orthogonal to Θ and reveals the total peculiar velocity of each object (shown as circles in Fig. 3). In these figures, we show data from different kinds of HB stars and it is clear that their kinematics are quite dissimilar. Actually, we found a trend in the kinematics of blue HB stars (Altmann & de Boer 2000). Apart from these diagrams, there are many other ways to discriminate stars belonging to different populations.

A study of the current velocities and positions of a sample of stars can thus reveal a wealth of information about it's kinematics and population membership. The second part will add information of kinematics over time, i.e. orbits to the procedure, giving us more tools of analysis at our disposal.

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