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

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RESUMEN

Si se parte del principio que la Vía Láctea constituye un buen prototipo de otras galaxias, esta 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. En esta segunda parte dirigimos nuestra atención hacia la integración de la cinemática de las estrellas en el tiempo, i.e. las órbitas.

ABSTRACT

Assuming our Galaxy to be roughly prototypical of other galaxies, it offers us a unique opportunity to make depth studies of Galactic structure. Unlike any other galaxy, it allows us to study the full kinematics of its stars. In this second part, we focus on the integration of kinematics over time, i.e. orbits.

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

1. INTRODUCTION

The first part (also in this volume) focuses on current kinematics and mentions some basic considerations concerning undertaking a kinematical study. In this part, we go a step further and integrate the kinematics over time in a galactic potential, i.e. analyse orbits. Finally, some examples for such studies will be given. For an introduction to the scientific questions involved, see part I.

2. ONE STEP FURTHER: ORBITS

As shown in Part I, analysing the current velocities can already reveal significant information about the kinematics, and hence, the population membership of a sample of stars. Integrating the motions of a star over time, i.e. calculating an orbit gives us several new tools. Among these, there are the apo and perigalactic distances (R_a, R_p), i.e. the largest and smallest distance of an object to the Galactic centre, the eccentricity of an orbit (*ecc*), and the largest distance to the Galactic plane ($z_{\max}$). Since the potential of the Galactic disk diminishes with distance from the Galactic centre (G.c.), orbits further away from the G.c. tend to widen up; consequently, they reach larger z. For this reason, de Boer et al. (1997) introduced another quantity, called the normalised z-extent[2] (*nze*), which is $z_{\max}$ divided by the planar distance (which is usually called ϖ or ρ). Orbits are often depicted in the form of a meridional plot, plotting ϖ against Z (see Fig. 1). From this plot, relevant quantities can easily be derived.

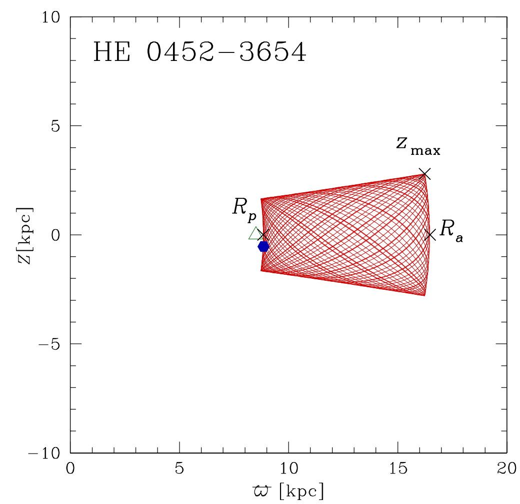

Fig. 1. Meridional cut representation of a typical box type orbit. Since the orbit of this object, sdB star HE 0452-3654, extends to almost 3 kpc, it is most likely a member of the thick disk. The full hexagon shows its current position and the triangle shows the Sun's position. The × symbols show the peri and apogalacticon as well as $z_{\max}$ and the according ϖ. From this, *ecc* and *nze* can be derived.

In order to calculate an orbit, one needs to know the potential of the Milky Way, i.e. its mass distribution. While this is not known entirely (especially since even the distance between G.c. and Sun and

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[2] note that z means a distance, while Z denotes the coordinate Z.

the local circular velocity are not accurately measured), a few potential models exist. But, because of these inherent uncertainties, the question arises of how well a potential model actually can model the real mass distribution of the Galaxy? How accurate are the resulting orbits? In most of our previous work, we used the potential of Allen & Santillan (1991, AS). To analyse the dependence of orbits from the potential model, Kaempf et al. (2005) conducted tests with additional models taken from Dehnen & Binney (1998, DB). While there are some differences, they in principle show overall agreement. Fortunately, the influence of the potential model, while not being negligible, is far from dominant.

A few warning words about orbits are in place at this point. Calculating an orbit over a given time (e.g. 10 Gyr) does not lead to an accurate representation of the trajectory of a star over that timespan. Regarding measurement errors, the Galactic potential (see above) will add up and lead to increasingly larger discrepancies between actual and predicted position. Moreover, the mass distribution of the Galaxy itself has changed over time, either by interactions or internal mass redistribution (accretion, bar formation and destruction, etc.). This means that an orbit is a representation of the *overall* characteristics of a stars trajectory in a potential constant in time - a long timespan is needed to get enough data points and to see what space the object actually occupies (some stars with halo orbits need a long time to travel through all the volume their orbits can occupy). For short timespans, i.e. 100 Myr and shorter, one can use the orbit as a representative trajectory, but one should conduct a very careful analysis of the errors in order to justify any conclusion drawn from this.

In general, stars with disk orbits occupy only a small space in the meridional plot, their nze and ecc are small. Thick disk orbits often extend to larger z and are more eccentric ($ecc > 0.15$). However, up to now, we have not been able to unambiguously separate thin and thick disk by analysing their orbits, as there seems to be a significant overlap between the two populations. Halo orbits usually have large eccentricities and often (but not necessarily so!) large $z_{\rm max}$. Some stars travel almost to the G.c. - others reach far beyond the solar circle.

2.1. *Deriving scale heights from orbits*

As a final step, orbits allow us to study the vertical distribution of stars. This is a very important parameter of a galaxy, and can also give insights on whether there have been interactions between a galaxy, e.g. the Milky Way and others, smaller entities - revealed by the presence of more than one disk. For the case of our Galaxy, evidence for such an additional disk - the so called thick disk[3] - has been accumulated over many years.

Since every sample is an ensemble of stars, which are currently near the Sun by chance, one can conclude that they are representative of the distribution of this particular star type. An orbit holds the information about the probability that an object will be found at certain coordinates, e.g. the Z coordinate. A histogram over Z shows this probability, and summed up over all the stars, the Z-probability distribution of the complete sample is derived (Fig. 2, panel a)).

If the sample is representative, this is the Z-probability distribution of this particular star type. If this distribution is exponential (or consists of more than one exponential distribution), one can - assuming an exponential disk, fit a linear equation (or more than one) to the logarithmic distribution and derive the scale height of this distribution (Fig. 2, panel b). For a sample of sdB stars, we found two distributions in this way, one with a scale height of 0.9 kpc and the other with 6-7 kpc (Altmann et al. 2004). If the stars belong to a good tracer, the scale heights, for instance, the thick disk can be obtained by this way. The smaller of the two values is rather similar to what other studies relying on other techniques and other tracers tend to find. Note, however, that there is significant spread in the scale height values found in the literature.

Again, one has to consider that an important ingredient is the Galactic potential model - the shortcomings of which could possibly alter the scale heights. This was also tested by Kaempf et al. (2005) after comparing results by using AS and DB models. They arrived to the conclusion that while there are some differences the results are not significantly different.

3. SELECTION EFFECTS

Kinematic analyses are affected by the selection of the sample. Often objects close to the Galactic plane are underrepresented. The reason for this is that many of the original candidate sources, e.g. the PG catalogue (Green et al. 1986), avoid low Galactic latitude because the larger amount of extinction is an obstacle for their primary goal - the search for QSO and other extragalactic sources of interest. Additionally, the volume covered by bright local stars is

[3]Majewski (1993) refers to the thick disk as intermediate population II (iPII).

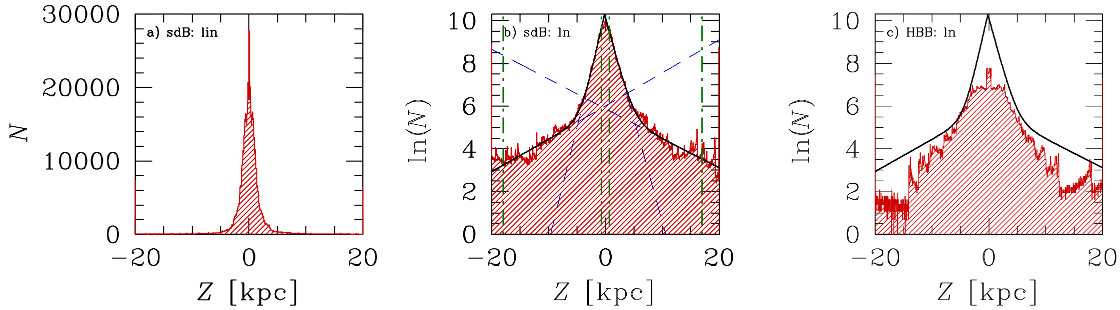

Fig. 2. The vertical distribution as derived from orbits. Panel a) shows a linear histogram of the sample of 114 sdB stars from Altmann et al. (2004) - the lack of stars in the middle can clearly be seen (the sharp peak is caused by one orbit alone), panel b) depicts the logarithmic distribution of the same sample, here the two slopes are evident. The solid lines represent the 2-component fit, and the dashed lines two linear equations fit to the slopes. The vertical dashed dotted lines show the fitting intervals for the 2-component fit. Panel c) shows the histogram of a sample of HBB stars which were at mostly greater distances than the sdB stars to demonstrate the effects sample selection. Here even the thick disk component is almost completely missing. The line plotted over the distribution is the 2-component fit of the sdB sample, showing that there are similarities in the distributions nonetheless.

very small and many data sources also have an upper brightness limit. Therefore, studies tend to under-represent stars not reaching to large distances from the Galactic plane, completely suppressing stars not venturing beyond a certain distance, as apparent in Fig. 2 c). This distance and the z range of stars, not reliably represented, depend mainly on the absolute magnitude of the tracer and the characteristics of the source from which the sample was chosen (e.g. low $|b|$ coverage, lower magnitude limit, etc.).

On the other hand, a sample of very nearby stars will lead to the effect that only very few stars, which venture very far from the plane, will be in the sample. The halo stars will mostly be those that despite their populatory nature, stay rather close to the disk. The reason for this is that stars tend to stay longer at extreme points of the their orbits, most noticeably at the apogalacticon and near z_{max}.

Because of these two effects, one sample often does not suffice in answering all questions. A very local sample may be better to discern the two disk populations, a sample of brighter, further away stars is more suitable for the derivation of scale heights and studies of the halo (also see part I).

4. EXAMPLES OF KINEMATICAL STUDIES

The studies of the kinematics of various types of HB stars conducted by our group (i.e. de Boer et al. 1997, Altmann & de Boer 2000, Altmann et al. 2004, Kaempf et al. 2005, and Maintz & de Boer 2005) have already extensively been mentioned in this paper. Summarising, these studies have established the population membership of the different HB types and found indications of a possible trend in, at least, the blue part of the HB, with sdB stars mainly being members of the thin and thick disk, and a minority of halo stars, and HBA and RR-Lyr stars being mainly members of the halo. At the red end, we again find more disk stars, but this part of the HB also contains HB stars with more than 1 $M_{\odot}$.

Another related study is concerned with White Dwarfs (Pauli et al. 2003, 2005). In the course of the Supernovae Ia Progenitor Survey (SPY, Napiwotzki et al. 2001), multiple spectra of several hundred WDs were taken. From these, radial velocities and distances were derived and served to find possible SNIa progenitor candidates. As a spin-off, the radial velocities proved to be an excellent database for a kinematic study. Together with own proper motions and others taken from literature, the kinematics of those WDs was analysed and several WDS were found to be halo members - the first halo WDs discovered by this method along with the object found by Méndez (2002) who used a somewhat different approach.

Star clusters, especially globulars, have been intensively studied. Their advantage is that since they consist of many stars, therefore far more accurate proper motions can be obtained than for single stars. Furthermore, they allow access to other important parameters, e.g. age (see Dauphole et al. 1996; Dinescu et al. 1997, 1999a, 1999b).

Another step further is the analysis of the kinematics of the Milky Way's dwarf satellite galaxies. The derivation of proper motions for these objects is a very difficult and challenging task - the nearest of these objects are nearly 100 kpc away. However, they belong to the objects which are more important and interesting to study, they can directly deliver clues, whether they are the fragments, whose infall formed the Galactic halo according to Searle & Zinn (1978). Moreover, issues of bursts of star formation observed in these objects can be addressed - do these bursts take place when the satellite is closest to the Galaxy? For several of these faint dwarf galaxies, proper motions have appeared, often contradicting each other (e.g. Piatek et al. 2003, and Dinescu et al. 2004).

As a final example, I would like to mention the various deep and wide field surveys. Most of them are primarily concerned with extragalactic issues, they do, however, present us with a treasure cove of data. Some, like the US-Chilean MUSYC survey (Gawiser et al. 2003) was - while also mainly addressing extragalactic problems - especially designed with a Galactic component in mind, in the form of multi epoch data being incorporated, eventually leading to proper motions of the stellar objects in the MUSYC fields. This will result in finding white and brown dwarfs, as well as other stars, with large proper motions, and in the end enabling us not only to identify such objects, but also to calculate their kinematics. Data from other surveys, which do not have data from more than one epoch, can be supplemented with new V or R data for astrometric purposes at relatively low investments in terms of observing time.

5. OUTLOOK & PERSPECTIVES

In these two papers, the quick overview of the methods and issues involved in the analysis of Galactic structure via kinematics was given. Many projects in this field require a significant investment in observational resources and also time - especially if the derivation of proper motions is involved. Since the CCD revolution, the difference between the two epochs required to get significant proper motions has decreased by almost an order of magnitude. However, this still means that such programmes take years[4] to accomplish. Observing time allocation, panels at the large international observatories are often reluctant to grant time to such projects. This is a chance for institutions with own observatories (for the proper motions or radial velocities one normally does not need large apertures). A large part of the data collection can be done using such telescopes dedicated to such a task. In the case of Chile, the access to larger telescope also provides a unique possibility, especially for programmes targeting rather faint stars. This means that Latin America, like the US, with it's number of national smaller observatories at relatively to very good sites has quite a potential of contributing in this field, especially in senseful collaborations with each other, Chile[5], and overseas (North America, Europe and elsewhere).

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[4]at least instead of life times.

[5]listed here separately, given it's special status.