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STRUCTURE OF THE HALO OF THE MILKY WAY

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RESUMEN

Describimos los últimos resultados y perspectivas futuras de la exploración QUEST de estrellas RR Lyrae en el halo de la Vía Láctea. Debido a que las variables RR Lyrae son excelentes estándares de luminosidad, éstas constituyen herramientas muy útiles para detectar sub-estructuras en el halo que puedan ser colas de marea de galaxias enanas o cúmulos globulares. También se muestra que las observaciones de estrellas RR Lyrae en la cola de marea de Sagitario ponen restricciones en la forma del halo de materia oscura de nuestra Galaxia.

ABSTRACT

We describe the latest results and future prospects of the QUEST survey for RR Lyrae stars in the halo of the Milky Way. Because RR Lyrae variables are excellent standard candles, they are very useful tools for finding sub-structures in the halo that may be tidal tails from dwarf galaxies or globular clusters. Also, we show that observations of the RR Lyrae stars in the Sagittarius streams provide constraints on the shape of the dark matter halo of our Galaxy.

Key Words: **GALAXY: FORMATION — GALAXY: HALO — STAR: VARIABLES: OTHER**

1. INTRODUCTION

Recent surveys of the galactic halo have shown that it does not have a smooth distribution of stars. Instead, several sub-structures have been found and some of them have been identified with the tidal disruption of satellite galaxies, such as the Sagittarius and the Canis Major dwarf galaxies. The remainder may be the debris from other galaxies or from globular clusters. The detailed study of sub-structures in the halo is necessary to understand how important the accretion of galaxies is in the process of formation of the halo of the Milky Way.

Particularly notable sub-structures in the halo of the Milky Way are the tidal tails of the Sagittarius dwarf spheroidal galaxy, one leading and one trailing from the main body of that galaxy. The long tidal streams from Sagittarius are distributed along a great circle around the whole sky (Majewski et al. 2003). The distribution of stars in the stream, both in space and velocity space, depends on the shape of the gravitational potential of the Milky Way, which is dominated by dark matter at large galactocentric distances. Thus, the Sagittarius streams or any other stream we may find in the future are a nice tool to determine if the halo of the Milky Way is flattened, as predicted by most cosmological models (e.g. Bullock 2002), or spherical.

There are several approaches to find and study sub-structures in the halo. Recent large-scale surveys try to isolate a particular type of stars and look for clumps in their spatial distribution in the sky. For example, the Sloan Digital Sky Survey (SDSS) has searched for over-densities of stars of spectral types A and F, which in the halo are mostly blue horizontal branch and turnoff stars respectively (Yanny et al. 2000; Newberg et al. 2002). M giant stars that belong to an intermediate age and relatively metal rich population can be isolated by the photometry in the 2-Micron All Sky Survey (2MASS) (Majewski et al. 2003). For instance, the Sagittarius dwarf spheroidal galaxy. The QUEST survey for RR Lyrae stars looks for excesses of this type of variables in the halo. Although RR Lyrae stars are less numerous than some of the tracers mentioned above, they have some characteristics that make them a prime tracer of the halo population: more importantly, they are good standard candles, hence they can provide excellent views of the spatial distribution of the clumps or streams. In addition, because RR Lyrae stars are very old, they trace not only the parts of the streams that were detached from the parent galaxy during its most recent perigalacticon passage, but also the older parts that were removed during previous orbits. In this article, we describe the QUEST survey for RR Lyrae stars, its future prospects and its implications in our understanding of the structure of the Galactic Halo.

2. THE QUEST SURVEY

The survey uses the QUEST camera (Baltay et al. 2002) installed at the Jurgen Stock Telescope (a

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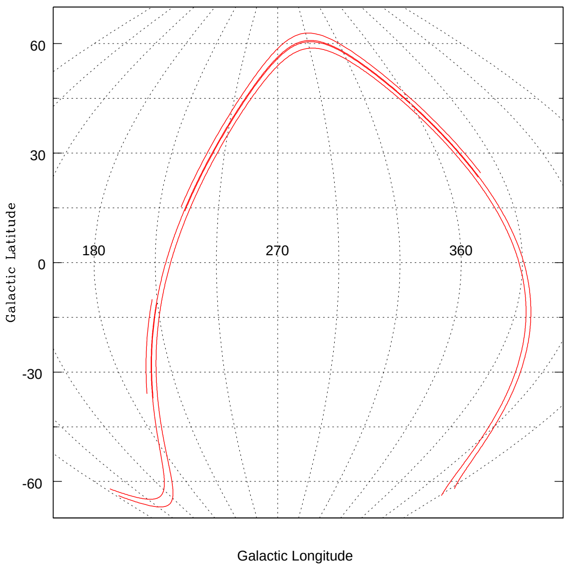

Fig. 1. Galactic coordinates of the complete region of the survey. The two strips correspond to scans centered at $\delta = -1^\circ$ and $\delta = -3^\circ$.

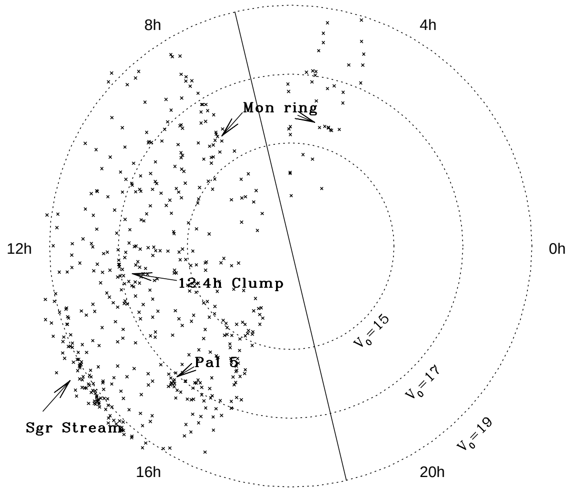

Fig. 2. Radial plot of the distribution of the 498 RR Lyrae stars in right ascension. The radial axis is the extinction corrected magnitudes, V_0. The circles correspond to a distance from the Sun of 8, 19 and 49 kpc. The solid line indicates the position of the galactic plane.

1-m Schmidt telescope) at the Venezuelan National Observatory of Llano del Hato. The camera, an array of 4 × 4 CCDs, is designed to work in driftscan mode which is a very efficient way to survey large areas of the sky. We scan the equatorial sky at a fixed declination. Each night we observe a long strip of the sky, spanning several hours in right ascension and 2.°3 in declination, in 4 different bandpasses.

The first part of the RR Lyrae survey used data from the QUEST collaboration[4], whose main goal was to survey the equatorial sky for quasars. For a variety of reasons, multi-epoch observations of an area of ∼ 400 sq deg were obtained by the team. Then, after the quasar survey was moved to the Schmidt telescope at Palomar Observatory with a new larger detector (Djorgovski et al. 2004), we continued using the equipment in Venezuela to make a large-scale variability survey that spans an additional area of ∼ 800 sq deg with time separations from days up to 4 years. Both parts of the survey use the same observational technique and data processing. Figure 1 shows the total region covered by the survey in galactic coordinates.

The bright and faint V magnitudes of the survey are 13.0 and 19.7 respectively, which converted in distances from 4 to 60 kpc for RR Lyrae stars. Depending on the region, we have from 20 to 60 epochs, which are enough to determine periods and other light curve parameters.

The first part of the survey detected 498 RR Lyrae stars in the halo, 86% of these stars were new discoveries. Details of the method to identify the variables, the completeness of the survey, the catalog and light curves can be found in Vivas et al. (2004). A summary of the main results from this first catalog is given in the next section. Observations for the remaining 800 sq degrees have been almost completed and we are presently processing the data.

3. RESULTS

3.1. *Radial profiles*

We have calculated the number density of RR Lyrae stars as a function of galactocentric distance for several directions in the sky, both at low and high galactic latitudes. A spherical halo with a power law drop off provides a poor fit to these data. A much improved fit is obtained through the model of Preston, Schectman & Beers (1991) which they found was a good match to RR Lyrae variables in the Lick survey. In their model, the density contours are ellipsoids that become systematically rounder with increasing R_{gal}, and the density fall-off is a power law of the semi-major axes. A good fit to our data is obtained with a flattening (c/a) of 0.5 near the galactic center, 1 at $R_{gal} > 20$ kpc and an exponent of -3.1 ± 0.1. Since there is no sign of a steepening

[4]The QUEST collaboration included Yale University, Indiana University, CIDA and Universidad de Los Andes.

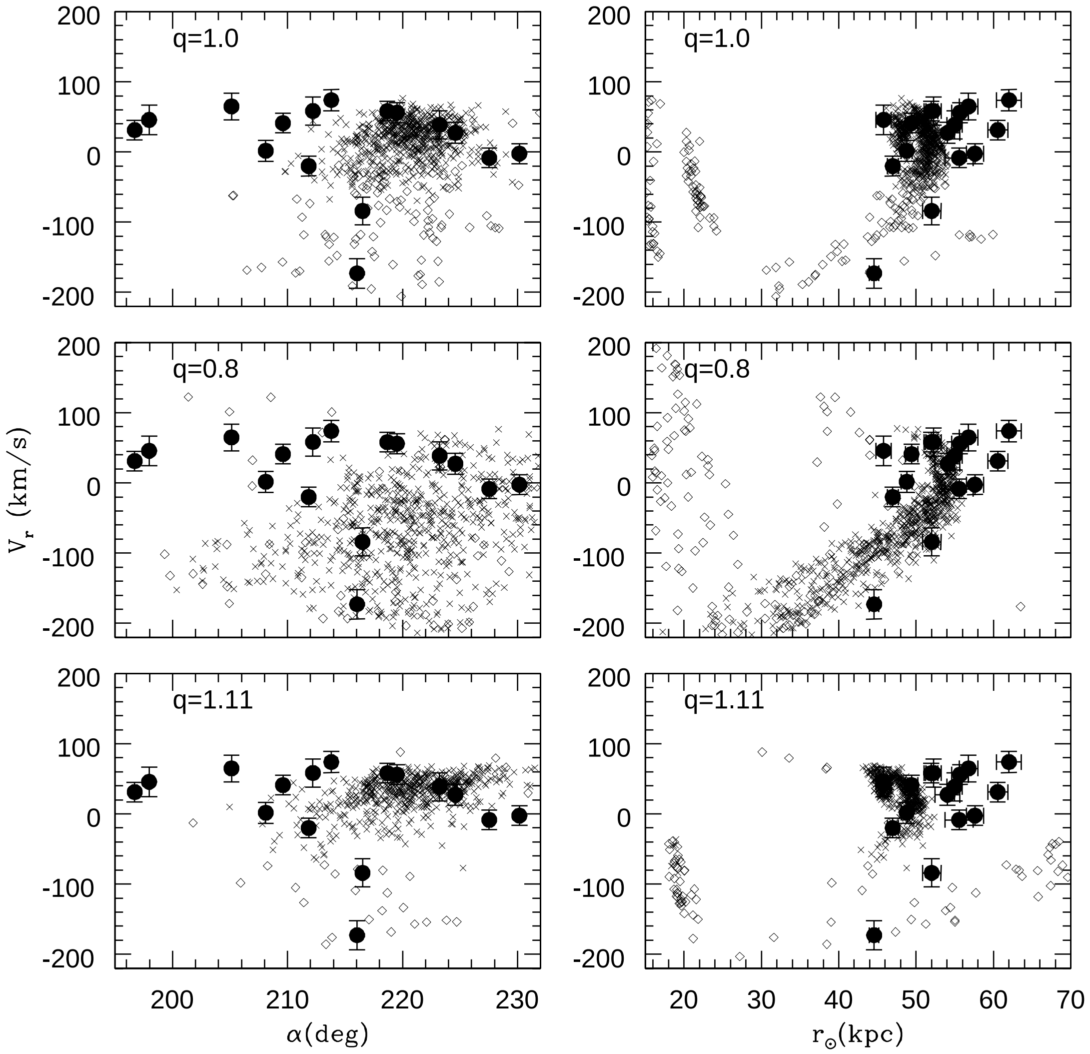

Fig. 3. The heliocentric radial velocities of the RR Lyrae stars (solid circles) in the leading tail of the Sagittarius stream as a function of right ascension and distance from the Sun. The observations are compared with the models of Helmi (2004) for three different shapes of the Milky Way Halo. The $\times$'s are model particles that were liberated from the galaxy during the last 3.5 Gyrs. Open diamonds are particles that became unbound between 3.5 and 7 Gyrs ago. Note that the spherical (q=1.0) and prolate (q=1.11) halo models reproduce the narrow velocity and distance distributions better than the oblate (q=0.8) one.

of the density decline, the stellar halo extends to at least 60 kpc.

3.2. *Sub-structures in the Halo*

The distribution of the RR Lyrae stars in the halo is, however, far from uniform. We have found several sub-structures. They show up as significant excesses of stars with respect to a halo background, as long as we follow a power law like the one described above. The distribution of the RR Lyrae stars in the sky is shown in Figure 2.

The most significant of these sub-structures is the tidal debris from the Sagittarius dwarf spheroidal galaxy, which is located 50 kpc from the galactic center.

Other strong sub-structure is very likely associated with the globular cluster Palomar 5, located at 17 kpc from the galactic center. The presence of two long tidal tails shows evidence that this globular cluster is being disrupted by the tidal forces of the Milky Way (Odenkirchen et al. 2002). This fact is confirmed by the excess of RR Lyrae stars around

Palomar 5, although not all of the RR Lyrae stars lie along the tidal tails (Zinn et al. 2004).

Another significant sub-structure, which we have called the $12^{\rm h}.4$ clump, has still an unknown origin. This group is located at 18 kpc from the galactic center and part of it lies in the foreground of the Sagittarius tidal stream. Its relationship with Sagittarius has yet to be demonstrated. Assuming different shapes for the potential of the Milky Way, theoretical models of the debris from Sagittarius predict some, or none, stream stars in this part of the halo (Law, Johnston & Majewski 2005).

Smaller sub-structures have also been found in the QUEST survey (see Fig. 2) near the detections of the Monoceros ring by the SDSS (Newberg et al. 2002).

3.3. *The shape of the Dark Matter Halo*

The Sagittarius stream provides a tool to measure the shape of the Milky Way's gravitational potential at large galactocentric distances that it is presumably dominated by the dark matter. Several numerical simulations of the disruption of Sagittarius are available in the literature (Ibata et al. 2001; Helmi 2004; Martinez-Delgado et al. 2004; Law, Johnston & Majewski 2005). To distinguish between models assuming different shapes, precise measurements of position, distance and radial velocity of stream stars are required. Because RR Lyrae stars are standard candles, they are ideal to test those models.

We have measured radial velocities of 16 of the QUEST RR Lyrae stars in the Sagittarius leading stream in VLT spectra (Vivas, Zinn & Gallart 2005). A comparison with the models by Helmi (2004) favors either a spherical halo or a prolate one, although the models do not reproduce the width of the stream in right ascension (Fig. 3).

4. THE FUTURE

An important aspect of the survey is the spectroscopic follow-up of the sub-structures (see also contribution by S. Duffau in this volume). Radial velocities are necessary to confirm that the structures are also coherent in space velocity, and together with the metallicities, will help us to look into their origin (for example, if they come from the destruction of dwarf galaxies or globular clusters). Also, detailed observations in other parts of the Sagittarius stream will be useful for constraining better the shape of the Milky Way's dark matter halo. We are obtaining spectra of a large number of the QUEST RR Lyrae stars with a variety of telescopes in Chile and the US.

The search of RR Lyrae stars in the new region observed by the QUEST survey may reveal other sub-structures in the halo.

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