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# SUB-STRUCTURES IN THE HALO OF THE MILKY WAY

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RESUMEN

Se describen los últimos resultados de la búsqueda QUEST de estrellas RR Lyrae. Esta búsqueda, la cual fue diseñada para encontrar y caracterizar sub-estructuras en el halo de nuestra Galaxia, ha cubierto aproximadamente 700 grados cuadrados del cielo y detectado 693 estrellas RR Lyrae, la mayoría de ellas descubiertas por primera vez en este estudio. La distribución espacial de las estrellas RR Lyrae ha revelado varios grupos interesantes en el halo. Algunos de ellos parecen estar asociados con la destrucción de galaxias esferoidales enanas (las colas de marea de Sagitario, la corriente estelar de Virgo, el anillo de Monoceros) o cúmulos globulares (Palomar 5), mientras que otros grupos tienen todavía un origen desconocido.

ABSTRACT

The latest results of the QUEST survey for RR Lyrae stars are described. This survey, which is designed to find and characterize sub-structures in the halo of our Galaxy, has covered about 700 square degrees of the sky and has detected 693 RR Lyrae stars, most of which are new discoveries. The spatial distribution of the RR Lyrae stars reveals several interesting groups in the halo. Some of them appear to be related to previous detections of the destruction of dwarf spheroidal galaxies (the Sagittarius tidal streams, the Virgo stellar stream, the Monoceros ring) or globular clusters (Palomar 5), while others still have an unknown origin.

*Key Words:* **GALAXY: STRUCTURE — GALAXY: HALO — STARS: VARIABLES: OTHER**



## 1. INTRODUCTION

Over the past few years, several detections of debris from disrupted galaxies have been made by surveys of the halo of the Milky Way (Newberg et al. 2002; Majewski et al. 2003; Yanny et al. 2003; Vivas & Zinn 2006, among others). Some of them are described elsewhere in this Volume (see contributions by S. Duffau and H. Rocha-Pinto). The debris is usually observed as an excess in the number density of different stellar tracers (e.g. M giants, F-type main-sequence stars, horizontal branch stars), and/or as groups of stars with similar kinematic properties. These results indicate that the density distribution of the stars in the Galactic halo is not smoothly varying, as was once believed. Ancient mergers with small satellite galaxies seem to have left a signature of intricate streams, as predicted by some theoretical models (Bullock, Kravtsov & Weinberg 2001; Bullock & Johnston 2005). Some small sub-structures may have been produced instead by the destruction of globular clusters (Odenkirchen et al. 2003; Grillmair & Dionatos 2006). To find those tidal streams and characterize their stellar populations are important for the understanding of the formation of galaxies like the Milky Way, and for constraining the theoretical models of hierarchical galaxy formation.

We present here the QUEST survey for RR Lyrae stars which is aimed to study the spatial distribution of this type of horizontal branch star in the halo. RR Lyrae stars are expected to be excellent tracers of tidal streams not only because they are good standard candles (hence, groups in the 3D halo are pinned down reliably) but also because they have been observed in all of the dwarf spheroidal (dSph) galaxies around the Milky Way (see Vivas & Zinn 2006). It is believed most mergers have involved that type of small galaxies (but see contribution by M. Catelan in this volume), and thus, presumably all streams contain a population of RR Lyrae stars.

## 2. THE QUEST SURVEY

The QUEST survey for RR Lyrae stars is being carried out with the 1m Jurgen Stock Telescope at the Venezuelan National Observatory of Llano del Hato. It uses the QUEST camera (Baltay et al. 2002), an array of 16 CCDs, in driftscan mode. We repeately scan strips of the sky of constant declination in several photometric bands. We use the V-band observations as the main bandpass for constructing time-series and recognizing RR Lyrae stars. The complete description of the survey and algorithms used for detecting RR Lyrae stars can be found in Vivas et al. (2004).

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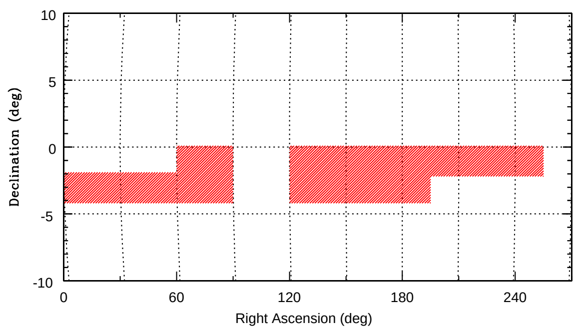


Fig. 1. Region covered by the QUEST survey for RR Lyrae stars in equatorial coordinates.

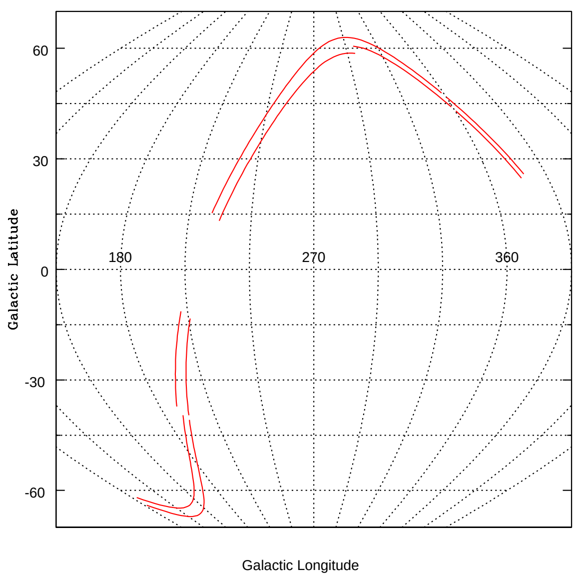


Fig. 2. Region covered by the QUEST survey in galactic coordinates.

### 2.1. *Observed Region*

To date, we have observed and analyzed $\sim 700$ square degrees of the sky, in two strips of constant declination near the celestial equator. The region observed is shown in Figures 1 and 2 in equatorial and galactic coordinates respectively. Since our main goal is to study the Galactic halo, we skipped a region near the galactic plane (around RA$\sim$ 7h at this declination). Nonetheless, the survey covers a wide range in galactic latitude. The data corresponding to the strip centered on $\delta = -1^\circ$ has already been published (Vivas et al. 2004).

### 2.2. *Known Problems*

The custom-made automated software for the detection of objects in the QUEST data has no capabilities for deblending close objects. We have discovered that blended objects may appear variable because of seeing variations and that several of the stars in the first QUEST catalog are not real RR Lyrae variables but blended objects. Most of these blends occurred in the regions of the lowest galactic latitude where crowding is more severe, which is also where the fewest number of observations had been made. With relatively few epochs available for each star, there was a greater chance that a fake variable might mimic the light curve of a RR Lyrae star and therefore be included in the QUEST catalog. Vivas & Zinn (2006) have eliminated all known blends from the catalog. At high galactic latitudes, only 1% of the variables were cases of blended images.

Another source of contamination in the first catalog was found after spectroscopic follow-up. We have found a few cases where the spectra of type c stars indicate much cooler than expected effective temperatures. Type c stars are always located in the blue side of the instability strip. These unusually cool type c variables are probably instead variable blue stragglers or W UMa eclipsing variables. Again, this type of contaminating object appears mostly at low galactic latitudes (see Vivas et al. 2004), and only for type c stars which are less common than the types ab.

## 3. SPATIAL DISTRIBUTION OF RR LYRAES IN THE HALO

Figures 3 shows the spatial distribution of the QUEST RR Lyrae stars in the regions where a single declination strip was surveyed. Thus, the observed region is a 2.2 deg wide strip of the sky. The radial axis in these plots correspond to extinction corrected V magnitudes, which is equivalent to distance from the Sun for RR Lyrae stars. The bright and faint limits of the survey enable the detection of RR Lyrae stars from $\sim 4$ and $\sim 60$ kpc from the Sun. The spatial distribution of the RR Lyrae stars (see also Figure 4) shows that the halo does not have a smooth distribution. Several sub-structures are present.

In particular, the Sagittarius (Sgr) tidal streams are seen in Figure 3. The plot in the right shows Sgr stream particles from the numerical simulations by Law, Johnston, & Majewski (2005) in exactly the same region of the sky as our observations. A very strong overdensity is located at $\sim 50$ kpc from the Sun, at $13 < \alpha < 16$ h. This is part of the Sgr leading tail, and it is clearly seen in our data (left plot). According to the model, there is also Sgr debris (part of the trailing tail) at $\sim 28$ kpc, between $0 < \alpha < 4$ h. The number density of this part of the trailing

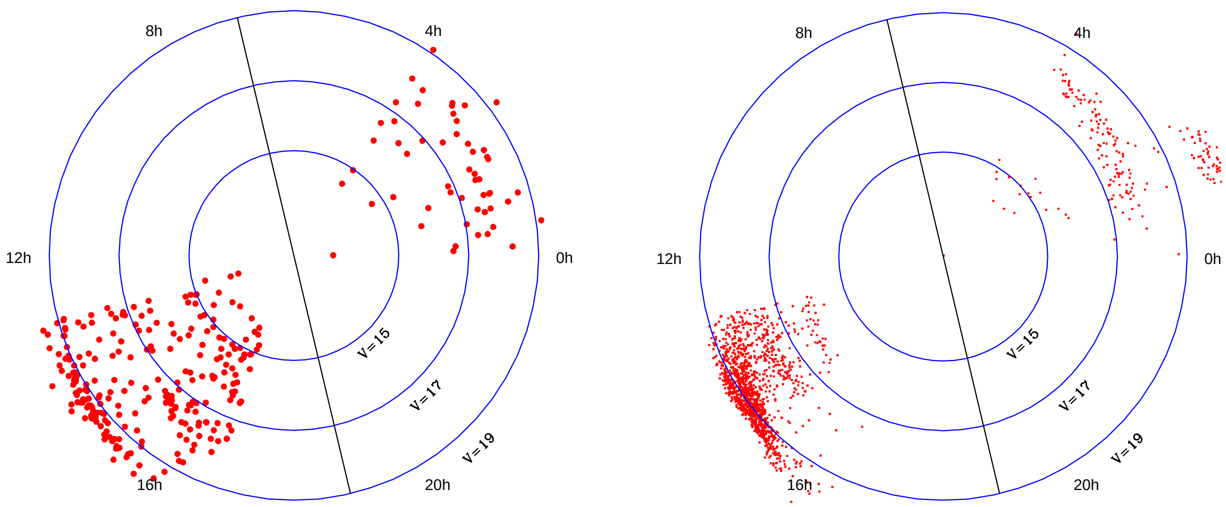


Fig. 3. Left: Distribution of the RR Lyrae stars in a slice of 2.2 deg wide. The region is, by coincidence, dominated by debris from the Sgr dSph galaxy. In the right plot we show the distribution of such debris as predicted by the numerical simulations of Law te al. (2005). The simulation shown assumes a spherical potential for the Milky Way's dark matter halo. In both plots, the circles correspond to a distance from the Sun of 8, 19 and 49 kpc.

tail of Sgr is about 1/10 of the density in the leading tail. This is the reason why it is not as obvious in the QUEST data. However, a more detailed look in our data indicates that there is indeed a peak in the number density of RR Lyrae stars at $V = 17.8$, which agrees with both the previous observations of this part of the tails with other tracers (Newberg et al. 2002; Majewski et al. 2003), and the Sgr models by Law, Johnston, & Majewski (2005), at least in the versions assuming either an spherical (Figure 3, right) or prolate shape of the dark matter halo of the Milky Way. The model assuming an oblate shape predicts the trailing tail at a closer distance. Measurements by Vivas, Zinn, & Gallart (2005) of the spatial and velocity distributions of the QUEST RR Lyrae stars in the leading tail of Sgr have also indicated that spherical and prolate models provide better fits to the data.

The QUEST data shown in Figure 3 includes also the globular cluster Palomar 5 (at $\alpha \sim 15^{\rm h}\!.3$, $V = 17.3$. Not only we recovered the 5 known RR Lyrae variables in this cluster, but we also discovered 2 new members. In addition, we detected a strong excess of RR Lyrae stars in the region surrounding the cluster. Most likely, these stars are related with the cluster which is known to be in the process of tidal disruption (Odenkirchen et al. 2003). In Vivas & Zinn (2006), we modeled the galactic background of RR Lyrae stars and used it to detect overdensities in the first catalog. The significance of these results

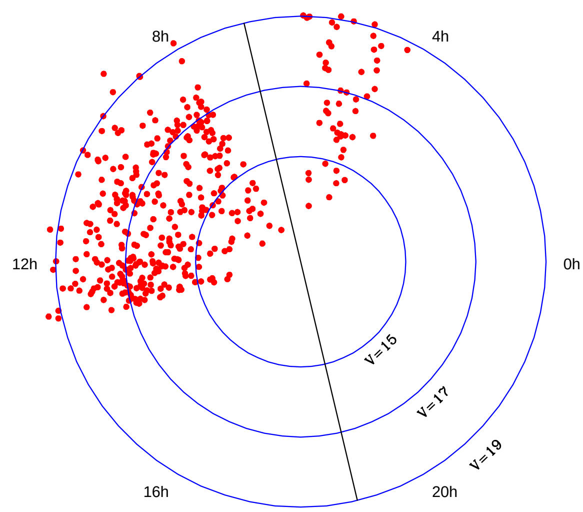


Fig. 4. Distribution of RR Lyrae stars in a slice of 4-deg wide. The big overdensity at $\sim 12$ hours of RA is due to the Virgo Stellar Stream and probably another sub-structures.

was investigated by using Monte Carlo simulations to find the likelihood that random variations alone can produce overdensities that are similar in size to the ones observed. Both the Sgr leading tail and the stars around Pal 5 appear to be significant overdensities.

In Figure 4, we show a slice of the sky that is $4^\circ$ wide in declination (includes two QUEST strips).

Because more stars are included than in the $2\overset{\circ}{.}2$ slice of the first QUEST catalog, the presence of substructure is more evident.

The strongest excess of RR Lyrae stars is seen at $12 < \alpha < 13$h and $V \sim 17$, which is equivalent to a distance of $\sim 20$ kpc from the Sun. This feature was observed before with just the first QUEST catalog (Vivas et al. 2001; Vivas & Zinn 2003), and in data from SDSS (Newberg et al. 2002). Spectroscopic observations of a sample of RR Lyrae stars in this region have suggested that part of this overdensity is the remnant of a disrupted dSph galaxy (see contribution by S. Duffau in this Volume, and Duffau et al. 2006). The newest QUEST data (Figure 4) indicates that the feature extends to the south and continues being a equally strong overdensity in the southermost part. Investigation of the radial velocities and metallicities of the rest of the stars in the region continues.

Figure 4 shows other sub-structures. A couple of them may have a common origin, the Monoceros ring (Yanny et al. 2003; Ibata et al. 2003). Our surveyed region crosses the Monoceros ring in two parts: at $\alpha \sim 4\overset{h}{.}8$, $V \sim 15.5$, and at $\alpha \sim 8\overset{h}{.}5$, $V \sim 15.7$. Both features were detected by our overdensity finding algorithm (Vivas & Zinn 2006), using only stars in the first catalog.

With the addition of the second QUEST strip, a new feature is now clearly visible at $\alpha \sim 10\overset{h}{.}5$, $V \sim 17.3$. It contains about 15 RR Lyrae stars closely located in the sky, at a mean distance of $\sim 23$ kpc from the Sun. Another possible large group is also seen at a similar magnitude, between $8 < \alpha < 9$h. Spectroscopy of stars in these groups is needed to confirm that they are indeed a coherent group in velocity space, and to investigate their origins.

## 4. CONCLUDING REMARKS

The results obtained so far by the QUEST survey indicate that RR Lyrae stars are powerful tracers of sub-structures in the halo. This is due in part to the fact that they are the best standard candles among the commonly used tracers of the halo population. The determination of radial velocity and metallicity distributions in the halo sub-structures is needed to understand the origin of the overdensities and to build a better picture of the accretion history of the Milky Way.

The QUEST survey will continue until covering $\sim 1200$ sq degrees of the sky. It will include a study at low galactic latitudes toward the Galactic anticenter in order to investigate the number density and extension of the thick disk population of RR Lyrae stars. In addition, a database containing the QUEST timeseries for several tens of thousands objects will be made available to the astronomical community.

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