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RR Lyrae Stars in the Halo: Tracers of Streams of Debris of Disrupted Galaxies *

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Abstract. We discuss the first part of a survey for RR Lyrae variables in the galactic halo that is being made with the 1m Schmidt telescope at the Venezuelan National Observatory. So far the survey has discovered 497 variables in 380 deg^2, lying from 4 to 60 kpc from the Sun. It has detected three statistically significant clumps of variables, which shows that outer halo does not have smooth density contours. One clump is located at 50 kpc from the galactic center, and it is probably tidal debris from the Sagittarius dwarf spheroidal galaxy. A second structure, at 17 kpc from the galactic center, appears to be due to the tidal disruption of the globular cluster Pal 5. The third group, at 19 kpc, is not related with any known globular cluster or dwarf galaxy. The little that is known about its properties is consistent with it being debris from a disrupted galaxy.

Key words. Galaxy: halo – Galaxy: structure – Stars: variables: other – Surveys

1. Introduction

Wide field imagers are essential tools for modern studies of the large-scale structure of the halo of our Galaxy since it is necessary to observe hundreds of square degrees of the sky. A second key ingredient is to use a tracer of the halo population that is easily separated from the numerous foreground stars belonging to the thin and thick disk populations. Among several other good possibilities, variable stars of the RR Lyrae type are ideal tracers. They are low-mass evolved stars and therefore, they trace the oldest stellar population (age > 9 Gyrs). They are well known standard candles, which make them ideal for studying the three-dimensional structure of the halo. And finally, they are very easy to recognize because of their large-amplitude variability (~ 1 mag) and relatively short periods.

In recent years our understanding of the structure of the halo has advanced significantly. It is now clear that at least the outer regions of the halo, do not have a smooth distribution of stars. Instead, the distribution seems to be quite clumpy (Newberg et al. 2002; Vivas et al. 2001; Yanny et al. 2000; Ivezic et al. 2000). The most likely in-

* Based on observations at the Observatorio Nacional de Llano del Hato, Venezuela

terpretation is that these sub-structures are relics of small satellite galaxies that have been accreted and destroyed by the tidal forces of the Milky Way. The stars (and globular clusters) of those disrupted satellite galaxies have formed a part, if not all of the halo of our Galaxy. This scenario is also consistent with theoretical models of hierarchical formation of structures based in cold dark matter cosmology (eg., Moore et al. 1999; Bullock, Kravtsov & Weinberg 2001).

In order to quantify how important was the accretion mechanism in the formation of the halo, we need to find and study the relics of these disrupted galaxies. Moreover, their study may reveal a relationship with the population of dwarf spheroidal (dSph) galaxies that still orbit the Galaxy. The ultimate goals are to determine the accretion history of the Galaxy and the fates of its retinue of past and present satellite galaxies.

We present here the first part of a large scale survey of RR Lyrae variable stars (RRs) aimed at studying the spatial distribution of stars in the halo, especially at large distances from the galactic center. This distant region of the Galaxy has been poorly studied in the past mainly because of the lack of wide field CCD cameras able to cover large regions of the sky, down to magnitudes faint enough to reach the far halo.

2. The Survey

Our RR Lyrae survey is being carried at the 1m Schmidt telescope at the Observatorio Nacional de Llano del Hato, in Venezuela. This wide-field telescope is equipped with a large format CCD camera known as the QUEST camera[1] (Baltay et al. 2002). The camera is designed to work in drift-scan mode, a very efficient way to perform surveys. Thus, each night of observation we obtain a strip of the sky, which is 2.°3 wide, and several hours of right ascension long, in four different filter bandpasses.

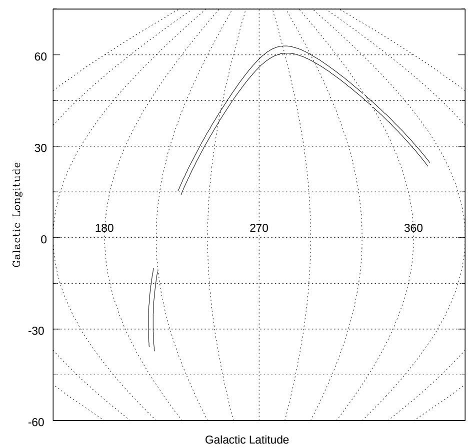

Fig. 1. Galactic coordinates of the region of the survey.

In order to maximize the science output of the survey, we were able to combine several different projects within the same observational scheme. Each of these projects required the repeated observation of the same large region of the sky to the faintest possible limiting magnitude. Aside from the RR Lyrae survey, some of the projects include: searching for quasars through variability, supernovas (Schaefer et al. 2001), transneptunian objects (Ferrín et al. 2001) and other solar system science, and T Tauri stars (Briceño et al, this volume).

The first part of the survey was centered at $\delta = -1°$ and covers a total of 380 deg^2 down to a depth of $V \sim 19.7$. It spans a large range in galactic coordinates (Figure 1), and reveals RRs lying between 4 and 60 kpc from the Sun. We obtained between 15 and 40 observations along each different line of sight. Due to the very high amount of data (~ 1.7 Terabytes), all the basic reduction, astrometry and aperture

[1] QUEST is an international collaboration (Yale and Indiana Universities (USA), and Centro de Investigaciones de Astronomía and Universidad de Los Andes (Venezuela)), whose main goal is to perform a large scale survey of quasars.

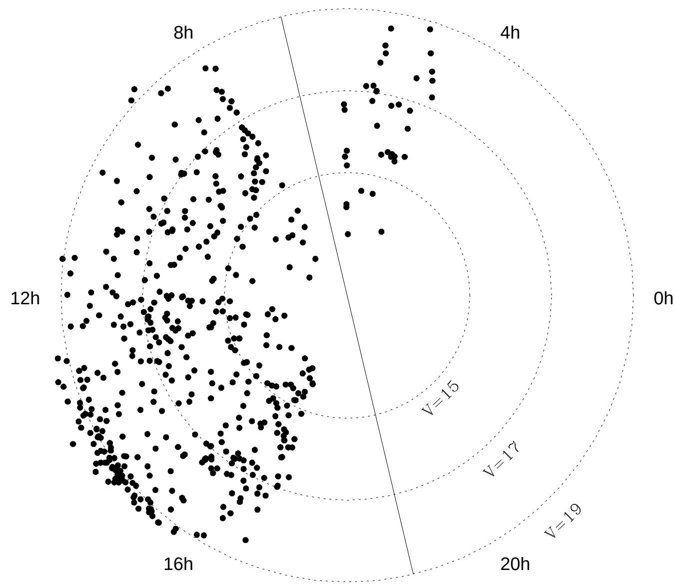

Fig. 2. Radial plot of the distribution of the RRs in right ascension. The radial axis is the extinction corrected magnitudes, V_0. All stars are located in a 2°.3 wide strip centered at declination $-1°10'.8$. The circles correspond to a distance from the Sun of 8, 19 and 49 kpc respectively. The solid line indicates the position of the galactic plane.

photometry was done with a custom made automatic pipeline.

We use relative photometry to construct time series of all objects in the V band. Variable objects were chosen using a χ^2 test. To isolate RRs we imposed further constraints on color (V-R$<$ 0.42), amplitude of variation ($0.2 < \Delta V < 1.6$) and period ($0.15 < P < 0.9$ days). Finally, visual inspection of the phased light curves was done to select RRs of type ab (asymmetric light curves) and type c (sinusoidal light curves). The completeness of the survey was estimated by extensive simulations of artificial light curves, and it is high ($>$ 80%) for the types ab but lower ($40-60$%) for the type c variables.

3. Results

We have found 497 RRs in the surveyed area, 86% of which are newly discovered objects. About 150 of these stars lie more than 30 kpc from the galactic center, which is a significant fraction of all the known objects at large galactocentric distances. For calculating the distances, we assumed an absolute magnitude for all RRs of $M_V = +0.55$ (Demarque et al. 2000), and extinction corrections from Schlegel, Finkbeiner & Davis (1998).

The spatial distribution of RRs can be seen in Figure 2. We calculated the space density of RRs as a function of galactocentric distance for different lines of sight, each covering a small range in galactic coordinates. In this way, we were able to study differences in the density profiles at different parts of the halo. This technique also enables us to detect easily over-densities or clumps in the halo (Vivas & Zinn 2002; Vivas 2002).

3.1. Shape of the luminous halo

Since our data spans a large range of both galactic latitude and longitude, we tested several models of the shape of isodensity contours in the halo, as a function of distance. The model that best fit the data has density contours that are flattened in the inner halo (galactocentric distance $R_{gal} <$ 20 kpc), and spherical at larger distances, as proposed earlier by Preston, Schectman & Beers (1991). However, a halo with density contours slightly flattened (c/a=0.9) in the outermost parts cannot be discarded.
The average space density of RR Lyrae stars between 4 and 60 kpc is well described by this power law:

$$\rho(a) = (4.2 \pm 1.5)(a/R_0)^{(-3.1\pm0.1)}\text{kpc}^{-3}$$

where a is the semimajor axis of ellipsoids around the galactic center.

There is no sign of a sudden fall off in the space density of RRs that would indicate the edge of the halo. Ivezic et al. (2000) claim that such an edge could be located at 50-60 kpc, which is right at the faint limit of our survey.

3.2. Clumpiness in the halo

The spatial distribution of RRs in our survey is clearly clumpy (see Fig. 2). In the range $R_{gal} = 20 - 50$ kpc, the variation in the number of RRs from one part of the sky to another is larger than expected from pure statistical fluctuations. Although the survey covers an area less than 1% of the entire halo, we have detected three strong sub-structures in the halo, which are described below. Figure 3 shows the Period-Amplitude diagrams for the RRs (type ab) in these three clumps.

The Sgr stream clump: is the largest clump found in the survey, which is probably a consequence of it being part of the present-day disruption of a dSph galaxy by the tidal forces of the Milky Way. The clump is part of the tidal debris of the Sagittarius (Sgr) dSph and it is located $\sim 60°$ away from the body of the galaxy. The 84 RRs in the clump have a mean magnitude of $\langle V_0 \rangle = 19.1 \pm 0.2$. The clump is located at 48 kpc from the galactic center and spans an area of about 78 deg^2, at $13^{\rm h}\!.0 < \alpha < 15^{\rm h}\!.4$. The depth along the line of sight is small, only ~ 4 kpc (Vivas et al. 2001). The presence of this structure has been detected by several surveys with different tracers (Newberg et al. 2002; Yanny et al. 2000; Ivezic et al. 2000; Ibata et al. 2001). The mean period of the RR Lyrae stars in the clump, 0.58 days, is similar to the value found in the central part of Sgr (Cseresnjes 2001).

The clump at $\boldsymbol{\alpha = 12^{\rm h}\!.4}$: this clump of 21 RRs, is located only 19 kpc from the Sun ($\langle V_0 \rangle = 16.9 \pm 0.2$). It also has high statistical significance (a 5σ overdensity compared to the smooth halo contours). This structure has also been detected as an excess of F stars (halo turnoff candidates) by Newberg et al. (2002) from the *Sloan Digital Sky Survey* (SDSS). The clump does not seem to be related with any known dSph galaxy or globular cluster. The mean period and period-amplitude distribution indicate that the RRs do not fit within one Oosterhoff group (Oo), which suggests that the clump may be the remnants of an ancient galaxy rather than a disrupted globular cluster. The radial velocities and metallicities of these stars are being measured, and they should shed more light on the origin of this clump.

The Pal 5 clump: the origin of this clump of 12 stars appears to be different from the other two. It is located in the same direction ($\alpha = 15^{\rm h}\!.3$) and at the same distance as the globular cluster Pal 5 ($\langle V_0 \rangle =$

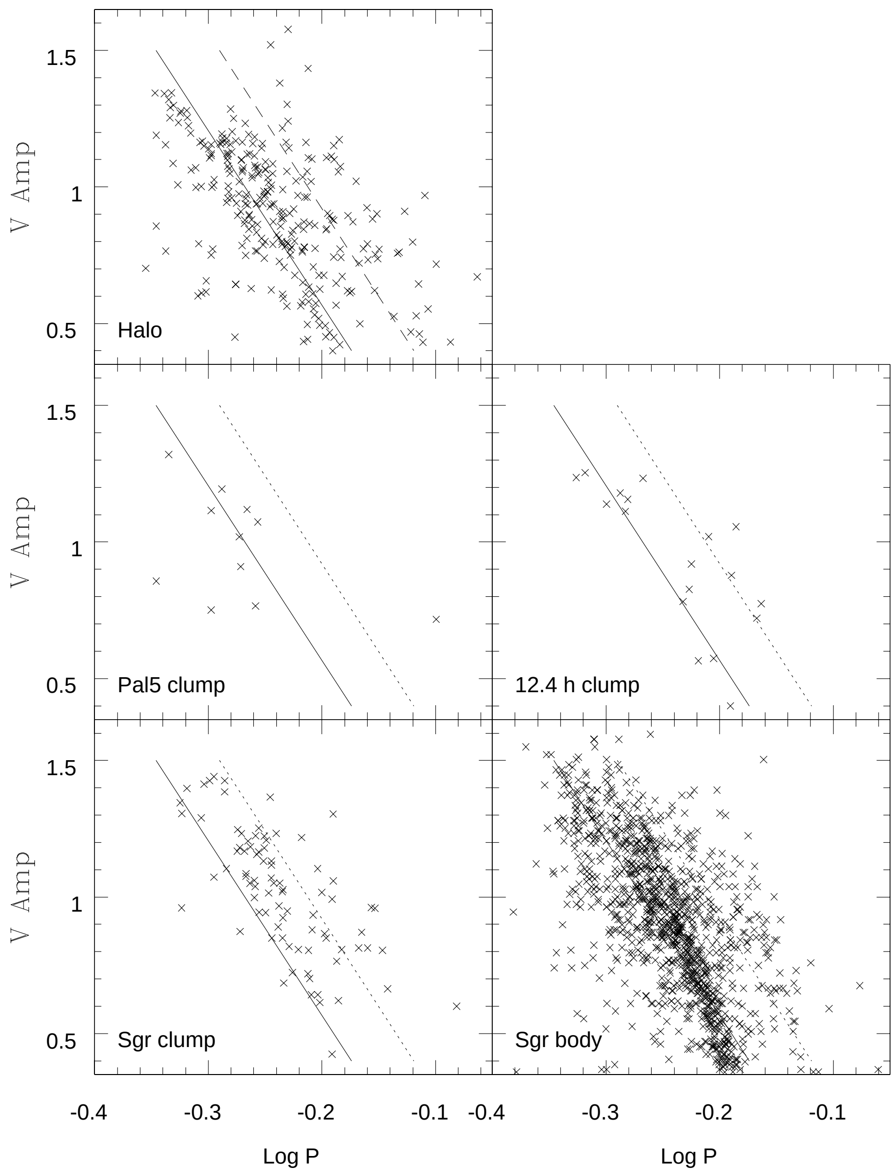

Fig. 3. Period-Amplitude diagrams of the major clumps found in the survey. For comparison, we show a diagram of the general halo RR Lyrae population (which does not include Sgr stream stars) and a diagram of 1194 RRs in the body of the Sgr galaxy from the survey by Cseresnjes (2001). The mean location of RR Lyrae stars (type ab) in the OoI globular cluster M3, and the OoII cluster M15, are indicated by the solid and dashed lines respectively.

17.1 ± 0.2). The properties of the RRs in the clump suggest an OoI classification, as is the cluster itself (Clement et al. 2001). A rough estimate of the metallicity of the group based on the mean period of the RRs is also consistent with measurements of cluster stars. Consequently, this group of RRs, which extends far beyond the tidal radius of the cluster, have all the right properties to be members of the cluster. The recent investigation by (Odenkirchen et al. 2001) has detected tidal tails emanating from Pal 5. However, our clump stars extend even farther away from the cluster and over a wider range of directions than the narrow tidal tails detected by Odenkirchen et al.

4. Conclusions

The streams and sub-structures found in the distribution of RRs in the outer halo of the Milky Way resemble the signatures of merger events. The outer halo is significantly clumpy and this is consistent with the idea that accretion of satellites played a major role in the formation of the outer halo.

Satellite dSph galaxies are the main suspect for being the building blocks of the halo. If so, the stellar population of the halo should resemble a composite of several dSph galaxies. The pulsational properties of the halo and these galaxies are indeed similar in that both have wide period-amplitude distributions and mean periods intermediate between Oo groups I and II. Although this may not constitute a strong proof that the halo RR Lyrae population came indeed from disrupted dSph galaxies, it is at least consistent with this hypothesis.

Our data have confirmed previous studies that showed that the inner halo is flattened towards the galactic plane. This may be evidence that the inner halo formed differently, perhaps as a dissipative collapse of a protogalactic cloud.

The search for streams in the halo by QUEST and other surveys like the SDSS still cover a small fraction of the sky. Several streams have been found but they are still few to allow a description of the accretion history of the Milky Way. We are continuing the RR Lyrae survey with the QUEST camera in a second declination strip. An important by-product of this survey will be a very large database of variable objects which will be made available to the astronomical community in the near future.

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