WHERE DOES THE DARK HALO OF THE GALAXY END?

M. Miyamoto, T. Tsujimoto
National Astronomical Observatory, Mitaka, Tokyo 181, Japan

ABSTRACT

We estimate the mass and the extent of our Galaxy with a massive dark halo from extreme spatial velocities of Hipparcos RR Lyrae stars and other velocity sources. We find the most extreme velocity in the range 420–480 km s^{-1} for the present sample. The galactic potential dominated by the massive halo is modelled simply by a spherical logarithmic one, in which the mass distribution is truncated at a galactic boundary. Contrary to the popular concept of 'escape' or 'bound', we introduce another extreme condition on trapped orbits, in which no star can leak out of the galactic boundary. Then, the above range of the extreme velocity gives the boundary radius of 50 kpc −100 kpc and the total mass of $5.5 \times 10^{11} M_\odot - 1.1 \times 10^{12} M_\odot$.

Key words: Local Marginal Velocity; Galactic Boundary; Galactic Mass; Dark Halo.

1. INTRODUCTION

It is known that in our Galaxy the rotation curve is approximately flat to a galactocentric distance as great as twice the solar circle radius at the least (Fich et al. 1989). The flat rotation curve extends presumably to a much greater galactocentric distance in the same manner as observed in large spiral galaxies (Rubin 1987 and references therein). The flat rotation curve implies that the total gravitational mass density behaves similarly as that of the isothermal gas sphere, while the luminous matter density decreases exponentially with the galactocentric distance. It is believed that the dominant gravitational matter in the outer part of the Galaxy is the dark matter, and a small fraction of luminous matter in the Galaxy is covered by a massive dark halo.

Then, a question arises: How far does the massive dark halo extend and how much is the total galactic mass? To answer this question, Carney et al. (1988, hereafter referred to as CLL) have utilized the local escape velocity of stars passing through the solar neighborhood. Assuming the spherical logarithmic-potential for the Galaxy, they have found the boundary radius and the total mass of the Galaxy to be ~ 40 kpc and $\sim 5 \times 10^{11} M_\odot$, respectively, corresponding to the local escape velocity ~ 500 km s^{-1} derived from their extreme velocity stars.

We re-examine the same problem on the basis of local extreme velocities of Hipparcos RR Lyrae stars together with those compiled by CLL, Cudworth (1990), and Layden (1995). In the present study we introduce, however, a different condition from CLL's on trapped orbits of stars in the Galaxy with a massive dark halo.

2. THE GALACTIC POTENTIAL

We assume that the total mass of the luminous matters is negligible, compared with that of the massive dark halo, and the galactic potential can be modelled simply by a spherical one, in which the mass distribution is truncated at the galactic boundary radius $r = r_*$. Then, the galactic potential $\Phi(r)$, corresponding to the flat rotation curve of the circular velocity V_c is given by:

$$\Phi(r) = \begin{cases} V_c^2 \ln(r_*/r) + V_c^2 & \text{for} \quad r \le r_* \\ GM_*/r = V_c^2 (r_*/r) & \text{for} \quad r > r_* \end{cases} \tag{1}$$

where M_* denotes the total mass of the Galaxy.

3. A CONDITION ON TRAPPED ORBITS

In the usual concept of escape from or bound to the gravitational potential $\Phi(r)$ (cf. CLL), the galactocentric velocity of stars at the galactocentric distance r is limited by the inequality:

$$V_r^2 + V_t^2 \le 2\Phi(r) \tag{2}$$

where V_r and V_t denote the radial and tangential components of the velocity, respectively.

The above concept means that stars at the solar vicinity with a velocity larger than the escape velocity $\sqrt{2\Phi(r)}$ should reach an infinite distance from the Sun, taking an infinite time longer than the cosmological age, and the luminous matters (stars) proper to the Galaxy extend to infinity, while the extent of the dark halo is finite. On the other hand, if the

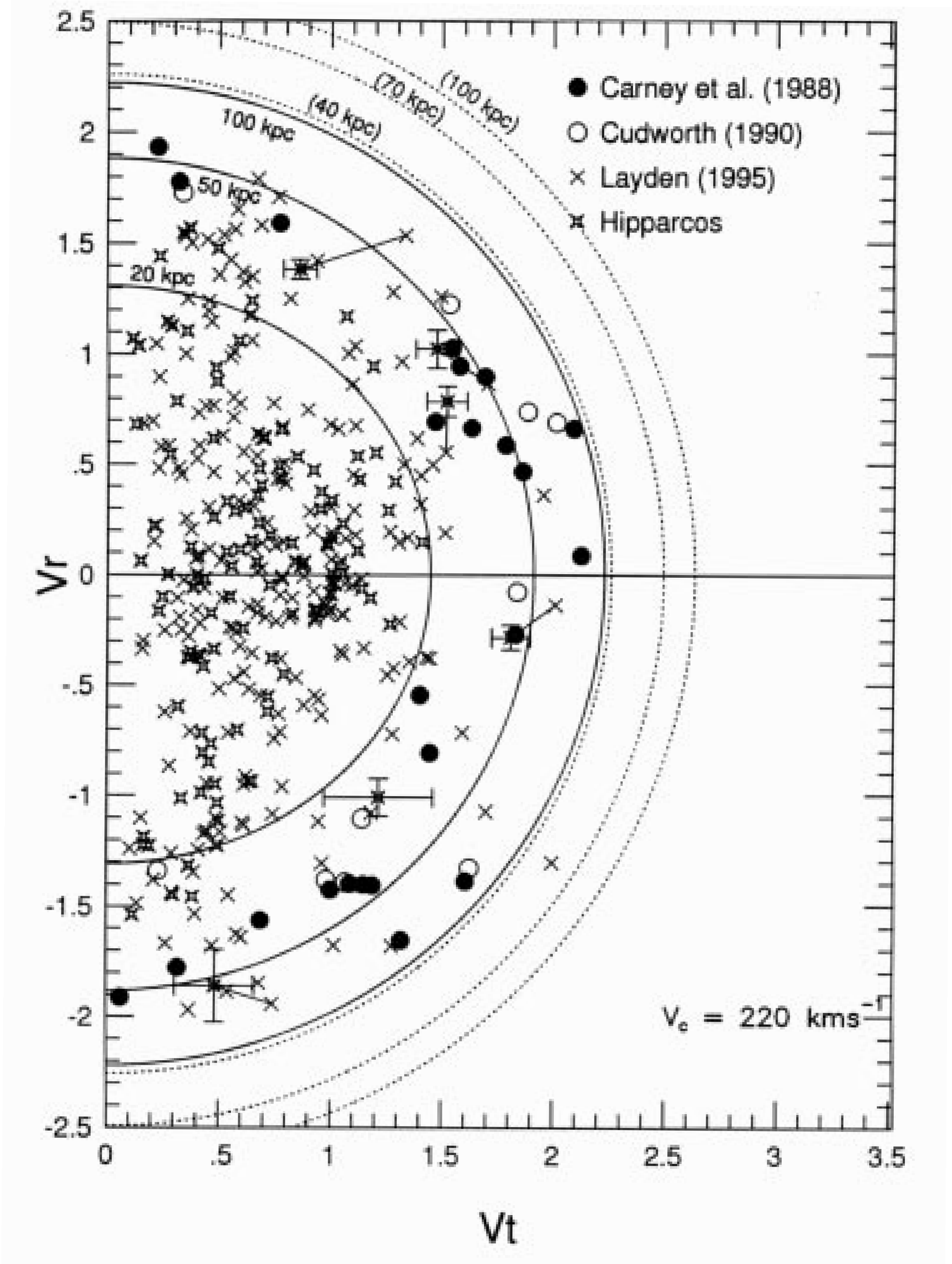

Figure 1. The velocity space (V_r, V_t) at the Sun $r = R_0$. The velocity components V_r and V_t are measured in units of V_c. The marginal velocities given by Equation 4 are shown by the solid ellipses, and the usual escape velocities by the dotted circles for the indicated boundary radii r_*, respectively. The sources of velocity plots are indicated in the figure.

luminous matters proper to our Galaxy have been arranged within the contracting dark halo of a finite radius, then the luminous matters should distribute out to the dark halo boundary, at the most. The wanderers or strays outside of the halo boundary are considered to be not proper to our Galaxy, due to disturbances of the local group of galaxies.

We incorporate this conceptual unit of the Galaxy into the definition of trapped orbits in the Galaxy, in such a manner that no star in the solar neighborhood ($r \leq r_*$) can leak out of the dark halo boundary at $r = r_*$, and stars with the local marginal velocity touch marginally the boundary. In this case, the boundary is composed of orbits with $V_{\rm r} = 0$, just like the boundary of liquid. Such an orbital state of stars near the boundary is supported by the fact that the velocity ellipsoid of outer halo stars is tangentially anisotropic (Sommer-Larsen et al. 1994). The present orbital condition at the boundary gives another local marginal velocity different from the usual escape velocity. Referring to the Lindblad Diagram (Chandrasekhar 1943), we find the condition under which the stars at r are confined within the galactic boundary at $r = r_*$:

$$V_{\rm r}^2 + \left(1 - \frac{r^2}{r_*^2}\right) V_{\rm t}^2 \leq 2\left[\Phi(r) - \Phi(r_*)\right] \qquad (3)$$

where the additional term $\Phi(r_*)$ in the right hand side makes a remarkable contrast with inequality (2).

Thus, the marginal velocity of stars at the Sun $r = R_0$ is given by:

$$V_{\rm r}^2 + \left(1 - \frac{r^2}{r_*^2}\right) V_{\rm t}^2 = 2V_{\rm c}^2 \ln(r_*/R_0) \qquad (4)$$

Equation 4 gives a family of the marginal velocity ellipses of the parameter r_* for a given set of R_0 and $V_{\rm c}$.

Note that putting $V_{\rm r} = 0$ in Equation 4, we have the maximum angular momentum attainable at $r = R_0$, which corresponds to the upper limit of the angular momentum J at $r = R_0$ for a given energy E in the Merritt velocity distribution function $f(Q_-)$ with $Q_- = E - J^2/(2r_*^2)$ (Merritt 1985).

4. THE BOUNDARY RADIUS AND TOTAL MASS OF THE GALAXY

In the following discussions, we take $R_0 = 8.5$ kpc and $V_{\rm c} = 220$ km s^{-1}, and the velocity components $V_{\rm r}$ and $V_{\rm t}$ are measured in units of the circular velocity $V_{\rm c}$. Figure 1 illustrates the velocity space ($V_{\rm r}$, $V_{\rm t}$) at the Sun $r = R_0$, in which the marginal velocities given by Equation 4 are shown by the solid ellipses, and the usual escape velocities by the dotted circles for the indicated boundary radii r_*, respectively. Note that the marginal velocity in the present case defines the boundary radius r_* larger than that given by the usual escape velocity, and the solid ellipses tend to circles as r_* increases.

In the present paper, the spatial velocities of Hipparcos RR Lyrae stars are obtained by combining the Hipparcos proper motions with the radial velocities and heliocentric distances compiled by Layden (1994). The other spatial velocity data are taken from Table II of CLL, Table II of Cudworth (1990), and Table 2 of Layden (1995) for RR Lyrae stars. The data sources of the velocity plots in Figure 1 are indicated in the figure, where the error estimates are marked only for six extreme velocities of Hipparcos RR Lyrae stars, and the lines joining cross and Hipparcos data indicate the identical RR Lyrae stars with improved proper motions. The poor number of extreme velocities of Hipparcos RR Lyraes cannot define a conclusive marginal velocity. Nevertheless, the extreme velocities around 420 km s^{-1} tell us that the boundary radius r_* of the Galaxy is larger than 50 kpc. If we include other velocity data (around 480 km s^{-1}) compiled by CLL, Cudworth (1990), and Layden (1995), then we have the boundary range 50 kpc $\lesssim r_* \lesssim$ 100 kpc.

When all of the Hipparcos data will be available, we will be able to delineate the boundary more clearly. Within the present limited Hipparcos data, we have the following preliminary conclusion:

The galactic boundary radius r_* is in the range:

$$50\text{kpc} \lesssim r_* \lesssim 100\text{kpc}$$

and the corresponding galactic total mass M_* is in the range:

$$5.5 \times 10^{11}\mathrm{M}_\odot \lesssim M_* \lesssim 1.1 \times 10^{12}\mathrm{M}_\odot$$

The present galactic extent and total mass considerably larger than those obtained by CLL attribute to replacement of the usual condition on trapped orbits with inequality (3).

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