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# THE GALACTIC ORBIT OF THE REMARKABLE HIGH-VELOCITY WIDE BINARY LDS 519

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RESUMEN. Se discute la naturaleza de LDS 519, una binaria abierta, de alta velocidad y cercana al Sol, y se dan argumentos en contra de un posible origen extragaláctico para este objeto. Se demuestra que su velocidad espacial es menor que la velocidad de escape si la galaxia posee un halo masivo; en consecuencia, se propone un origen galáctico para esta binaria. La órbita galáctica de LDS 519 se calcula numéricamente, empleando un modelo realista para la distribución de masa de la galaxia, el cual incluye un halo masivo y representa bien tanto la curva de rotación observada entre 1 y 60 kpc como la fuerza perpendicular al plano y los valores de las constantes A y B de la rotación galáctica. Incluso cuando se toman en cuenta las perturbaciones debidas a encuentros con nubes moleculares o con brazos espirales, LDS 519 permanece ligada a la galaxia durante tiempos hasta de $3.2 \times 10^{10}$ años. La órbita de este sistema confirma su carácter insólito; siempre cruza el plano galáctico con velocidades similares a su velocidad espacial actual, esto es, aproximadamente 465 km $s^{-1}$; además, alcanza distancias apogalácticas de más de 115 kpc y alturas sobre el plano de casi 20 kpc. Su período es de $1.3 \times 10^9$ años. Con base en la información proporcionada por la órbita de LDS 519 se propone un posible escenario para su origen.

ABSTRACT. The nature of the high-velocity, nearby, wide binary LDS 519 is discussed, and arguments are given against a possible extragalactic origin for this object. Its space velocity is shown to be lower than the escape velocity if the galaxy has a massive halo; therefore, a galactic origin for this binary is suggested. The galactic orbit of LDS 519 is numerically integrated using a realistic model for the galactic mass distribution that includes a massive halo and represents well the rotation curve from about 1 out to 60 kpc, the constants A and B of galactic rotation, and the perpendicular force. Even when perturbing effects due to molecular clouds or spiral arms are taken into account, LDS 519 remains bound to the galaxy over periods of up to $3.2 \times 10^{10}$ years. The orbit of this system confirms its unusual character: it always crosses the galactic plane with a galactocentric velocity similar to its present space velocity, that is, about 465 km $s^{-1}$; it reaches apogalactic distances of over 115 kpc, and z-distances of nearly 20 kpc. Its period is $1.3 \times 10^9$ years. On the basis of the information provided by the orbit a possible scenario for the origin of LDS 519 is proposed.

*Key words:* STARS-HIGH VELOCITY — STARS-BINARIES — GALAXY-ORBITS

## I. INTRODUCTION

The wide binary LDS 519 (whose other catalogue designations include GC 20393 and 20394; HD 134439 and 134440; BD -15:4041 and -15:4042; Gliese 579.2 A and 579.2 B; or SAO 159066 and 159067) is a common proper motion pair (Luyten 1941); both components also have a common radial velocity. The proper motion is large: a measured value of 3.67 arc seconds per year ranks LDS 519 among the objects of largest proper motion known. However, the parallax of LDS 519 was until recently rather uncertain; the measured values were discrepant: 0.048" (McCormick), 0.029" (Yale-Columbia) and 0.034" (Yerkes). More recent determinations have given significantly more accurate values for the absolute parallax: 0.037" ± 0.004" (Russell 1977) and 0.030" ± 0.004" (Heintz 1986). These recent measurements are essentially in agreement, so that the distance to LDS 519 can be considered to be well known. Adopting Heintz's value for the parallax the distance to LDS 519 is 33 pc. Since the radial velocity of this binary is known to be about 300 km $s^{-1}$ (Wilson 1953; Przybylski and Kennedy 1965), its space velocity relative to the galactic center can be computed. It turns out to be approximately 465 km $s^{-1}$.

The very large space velocity of LDS 519 could lead to the speculation that this binary is an extragalactic object moving through the solar neighborhood (Sky and Telescope 1986). The purpose of this paper is to investigate whether LDS 519 is bound to the Galaxy, and if so, to determine its orbital characteristics and its possible cosmogony. We give arguments that support a galactic origin for this binary. Using a recent mass model for the galaxy that includes a moderately massive halo (Allen and Martos 1986a), we show that LDS 519 is bound to the galaxy within generous limits. We compute the galactic orbit of this wide binary and we determine its dimensions, its character and its stability. We also inquire into the nature and possible origin of LDS 519 considered as a galactic object and we show that it belongs to the halo population. Its magnitude, colors and chemical composition support this identification. We conclude by speculating on some possible cosmogonic scenarios that could have given rise to high-velocity, low-metallicity objects like LDS 519.

Our approach is, in a way, similar to that used by Oort to establish the existence of the comet cloud: from the orbits of a very few, nearly-parabolic, comets observed close to the Earth, he estimated the extent of the comet cloud and its population. In a forthcoming paper, we attempt to derive further information about the extent and the population of the outer galactic halo on the basis of more numerous, but less precise, data on the kinematics of halo stars moving with extremely high galactocentric velocities.

## II. LDS 519: NOT EXTRAGALACTIC

The possibility that an object such as LDS 519 could be an extragalactic visitor just passing through the solar vicinity is very intriguing. However, it has to be taken with reservations. Although LDS 519 is unique in the solar neighborhood (there is no other star in Gliese's catalog with a comparable galactocentric velocity), other extreme-velocity stars are certainly known (see, for instance, Yoshii and Saio 1979; Carney 1984; Carney and Latham 1986; Sandage and Kowal 1986; Fouts and Sandage 1986). These stars, to be sure, are much farther away than LDS 519, and they lack accurate distance determinations (their parallaxes are usually photometric or spectroscopic). If we assume for a moment that the incidence of extreme velocity objects observed in the solar neighborhood is typical of intergalactic space we would have to conclude that it would indeed be very unlikely that a small volume of space around the Sun ($r < 33$ pc) should contain two intergalactic stars brighter than $M_V = 7$. This would imply that one in 1000 such stars is an intergalactic object, which in turn would translate into an intergalactic mass density $\rho = 8 \times 10^{-28}$ g $cm^{-3}$, more than two orders of magnitude larger than the critical density $\rho_c = 5 \times 10^{-30}$ g $cm^{-3}$ needed to close the Universe. The above numbers were obtained from the luminosity function derived by Wielen *et al.* (1983) for nearby stars, scaling the numbers they determined to a volume of 33 pc radius, the adopted distance to LDS 519. Note that in constructing this luminosity function, Wielen *et al.* counted each component of a visual double or multiple system as an independent star; for the sake of consistency, then, we count LDS 519A and B as two independent stars.

Under the same assumptions, we can compute the total light that would be contributed by hypothetical intergalactic objects such as LDS 519. The result is $L = 2.2 \times 10^{-6}\ L_{\odot}\ pc^{-3}$. This value can be compared to the total light due to galaxies, which is $L_G = 1.5 \times 10^{-10}\ L_{\odot}\ pc^{-3}$ (Peebles 1971). We see that if LDS 519 were a typical intergalactic object, the total light contributed by such objects would be more than $10^4$ times greater than that due to galaxies.

In view of these problems, we consider the alternative interpretation, namely that LDS 519 is bound to the galaxy, as far more likely, and we proceed to inquire further into the characteristics of its galactic orbit.

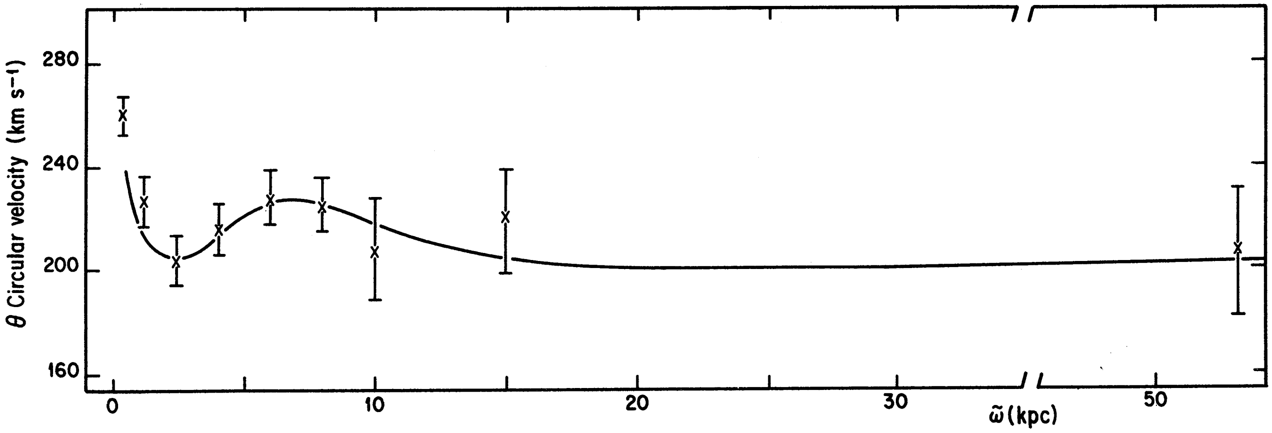

Fig. 1. The rotation curve resulting from the mass model of Allen and Martos (1986a). The observational points plotted are those advocated by Caldwell and Ostriker (1981) and Haud (1984). The error bars represent the estimated uncertainties.

## III. THE GALACTIC MASS MODEL AND THE ORBIT OF LDS 519.

A mathematically simple, yet realistic model of the mass distribution in our galaxy has been recently developed (Allen and Martos 1986). The proposed potential function $f(\tilde{\omega},z)$ is the sum of the potential functions of a central mass point, an ellipsoidal disk, and a massive spherical halo. The rotation curve resulting from this mass model (Figure 1) is flat from about 17 kpc out to 100 kpc, and represents a good fit to the observed values in the range 1 to 17 kpc (Caldwell and Ostriker 1981; Haud 1984). It is in excellent agreement to what the entire galactic rotation curve is believed to be like. With an adopted value for the total local mass density of 0.18 $M_{\odot}$ pc$^{-3}$ (Bahcall 1983) the resulting perpendicular force, $K_z$, agrees with observationally based determinations (Oort 1960; Bahcall 1984). The total galactic mass implied by the mass distribution is about $10^{12}$ solar masses, the total radius extends to 100 kpc. The computed values for Oort's constants of galactic rotation are A = 15.9 km s$^{-1}$kpc$^{-1}$ and B = -12.2 km s$^{-1}$ kpc$^{-1}$, and are thus within the range of modern observational determinations (Gunn, Knapp and Tremaine 1979; Caldwell and Ostriker 1981; Knapp 1983; Kerr and Lynden-Bell 1985). Our mass model thus represents the observations as well as other recent galactic mass models; its main advantage over other models is that with our potential function the forces at each point can be directly evaluated; there is no need for interpolations or numerical integrations; our potential function is also continuous everywhere, and has continuous derivatives; its simple mathematical form makes it particularly well suited for efficient and accurate numerical orbit computations.

The escape velocity computed from our mass model for objects in the solar vicinity is 546 km s$^{-1}$. Thus, in this mass model (and in others with a massive halo) LDS 519, with a total galactocentric velocity of 465 km s$^{-1}$, is well bound to the galaxy. Note that the model value for the escape velocity (546 km s$^{-1}$) is lower than the values usually derived for galactic mass models with massive haloes, which vary from about 550 km s$^{-1}$ to about 730 km s$^{-1}$ (Caldwell and Ostriker 1981). So, if we accept the existence of a massive halo (as almost everybody does, for good reasons) the binary LDS 519 turns out to be bound to the galaxy within generous limits, and it is not necessary to assume an intergalactic origin for it. However, its extremely high velocity raises questions as to how and where this object was formed. For these reasons, we decided to numerically integrate its galactic orbit.

The orbit was integrated backwards in time for 1.6 x $10^{10}$ years (the assumed upper limit to the age of the galaxy). The orbit was also computed forwards in time for another 1.6 x $10^{10}$ years, in order to have a more complete idea about its global character. The integration routine used incorporates a seventh-order Runge-Kutta-Fehlberg algorithm (Fehlberg 1968). Errors in the total energy and in the z-component of the angular momentum at the end of the run were of the order of $\Delta h/h \lesssim \Delta E/E \lesssim 10^{-7}$. The resulting orbit for the primary star

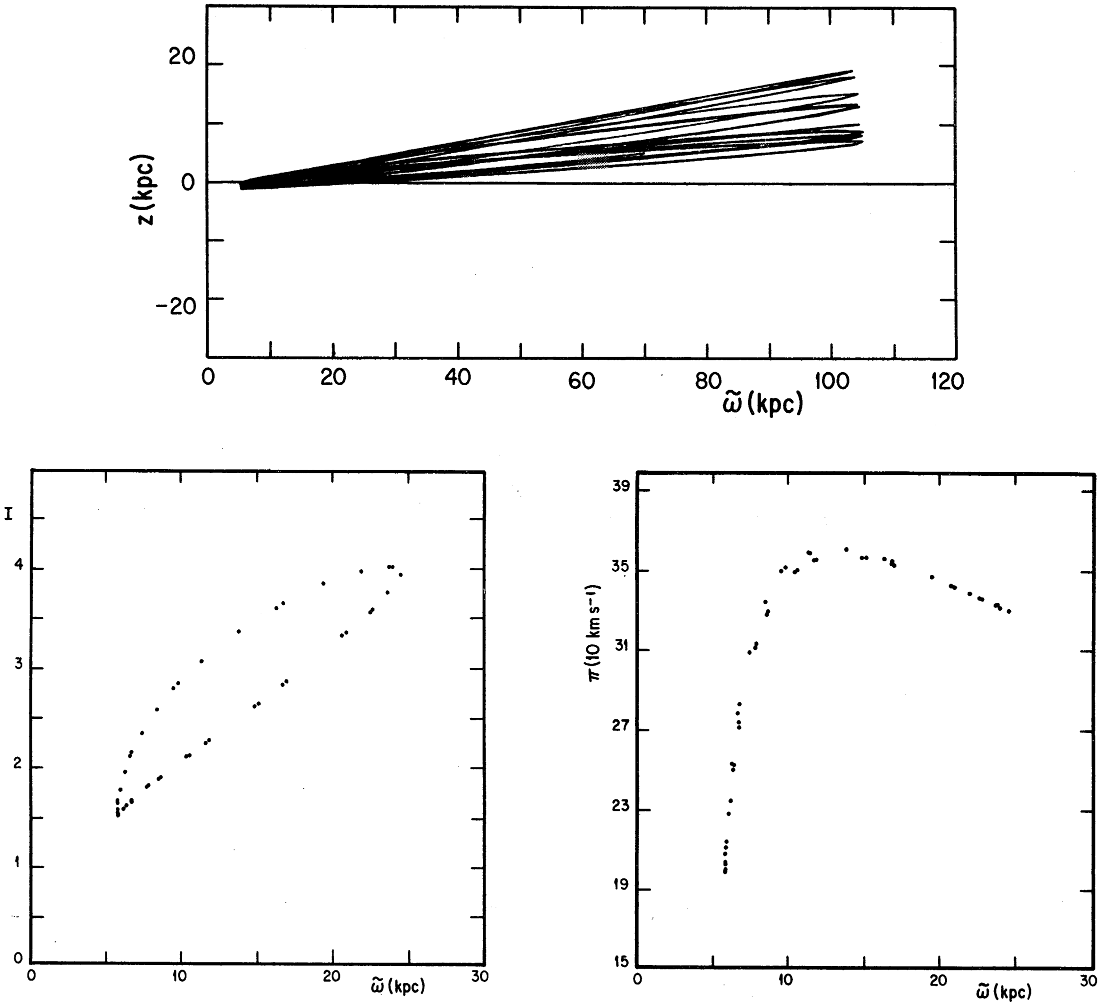

Fig. 2. (a) The meridional orbit of the primary, LDS 519A, run backwards in time for 1.6 × $10^{10}$ years. Figures 2(b) and 2(c) show the inclination diagram and the surface of section of this orbit.

(LDS 519A, HD 134439, or SAO 159067) is shown on the meridional plane in Figure 2a. Figures 2b and 2c show the inclination diagram and the surface of section for this orbit. These figures show that the orbit is of tube-type, probably not far from a stable periodic orbit. Table 1 lists the observed parameters of the primary star, Table 2 the assumed "initial conditions" for the computation, and Table 3 the resulting orbital characteristics.

To assess the effects on the computed orbit of observational errors in the input data used as "initial conditions" for the computation, we integrated independently the galactic orbit of the companion star. The differences in the measured proper motions and radial velocities of both components of this physical pair should be an indication of the observational errors that can be expected. The "true" values for the observed quantities are likely to be bound by the actual values determined for both components, which we used in our computations. The observed values for the companion are included in Table 1, the assumed initial values for the companion and the resulting orbital characteristics in Tables 2 and 3. The meridional orbit of the companion is shown in Figure 3a; Figures 3b and 3c show again the inclination diagram and the surface of section.

Although the orbits of both stars are not identical (see especially the inclination diagrams), the differences are slight; both orbits are qualitatively and quantitatively similar; both reach extreme and similar values of $\tilde{\omega}$ and z. We can safely conclude that the orbit is not

TABLE 1. OBSERVED DATA FOR LDS 519

| Star | LDS 519A | LDS 519B |
|---|---|---|
| Other Designations | GC 20394, BD -15:4042<br>HD 134439, SAO 159067<br>Gl 579.2 A | GC 20393, BD -15:4041<br>HD 134440, SAO 159066<br>Gl 579.2 B |
| $\alpha$ (1900) | $15^h7^m.5$ | $15^h7^m.5$ |
| $\delta$ (1900) | -16°08' | -16°13' |
| $\pi$ (") | 0.03 | 0.03 |
| $V_r$ (km $s^{-1}$) | +305.7 | +314.4 |
| $\mu_\alpha$ ("$y^{-1}$) | -1.024 | -1.020 |
| $\mu_\delta$ ("$y^{-1}$) | -3.530 | -3.534 |
| V | 9.12 | 9.47 |
| $M_v$ | 6.53 | 6.88 |
| U-B | 0.19 | 0.39 |
| B-V | 0.78 | 0.85 |
| U-V excess | 0.21 | 0.14 |
| [Fe/H] | -1.57 | -1.52 |
| Spectrum | K1 VI | K3 V-VI |

TABLE 2. "INITIAL CONDITIONS" FOR THE ORBIT OF LDS 519.

| STAR | U (km $s^{-1}$) | V (km $s^{-1}$) | W (km $s^{-1}$) | $\tilde{\omega}$ (kpc) | z (kpc) | $\Pi$ (km $s^{-1}$) | Z (km $s^{-1}$) | $\theta$ (km $s^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| LDS 519 A | 306.1 | -571.2 | -102.6 | 7.974 | 0.019 | -315.8 | -94.9 | -331.5 |
| LDS 519 B | 313.0 | -573.1 | -99.2 | 7.974 | 0.019 | -322.7 | -91.5 | -333.5 |

TABLE 3. PARAMETERS FOR THE ORBIT OF LDS 519.

| Star | Orbit | Final t ($10^{10}$y) | $\tilde{\omega}_{min}$ (kpc) | $\tilde{\omega}_{max}$ (kpc) | $z_{min}$ (kpc) | $z_{max}$ (kpc) | <Period> ($10^9$y) | "e" |
|---|---|---|---|---|---|---|---|---|
| LDS 519 A | forward | 1.6 | 5.20 | 105.24 | - 1.14 | 19.16 | 1.28 | 0.9058 |
| LDS 519 A | backward | -1.6 | 5.22 | 105.38 | - 1.14 | 19.11 | 1.28 | 0.9056 |
| LDS 519 B | forward | 1.6 | 5.19 | 111.88 | - 1.07 | 19.57 | 1.36 | 0.9113 |
| LDS 519 B | backward | -1.6 | 5.19 | 111.81 | - 1.07 | 19.49 | 1.36 | 0.9113 |
| LDS 519 A | forward, perturbed | 1.6 | 4.89 | 105.64 | -22.31 | 24.88 | 1.24 | 0.9115 |
| LDS 519 A | backward, perturbed | -1.6 | 5.01 | 110.69 | -15.69 | 23.19 | 1.26 | 0.9134 |
| LDS 519 B | forward, perturbed | 1.6 | 5.02 | 112.63 | -21.39 | 24.48 | 1.33 | 0.9147 |
| LDS 519 B | backward, perturbed | -1.6 | 4.96 | 115.80 | - 1.20 | 19.25 | 1.33 | 0.9179 |

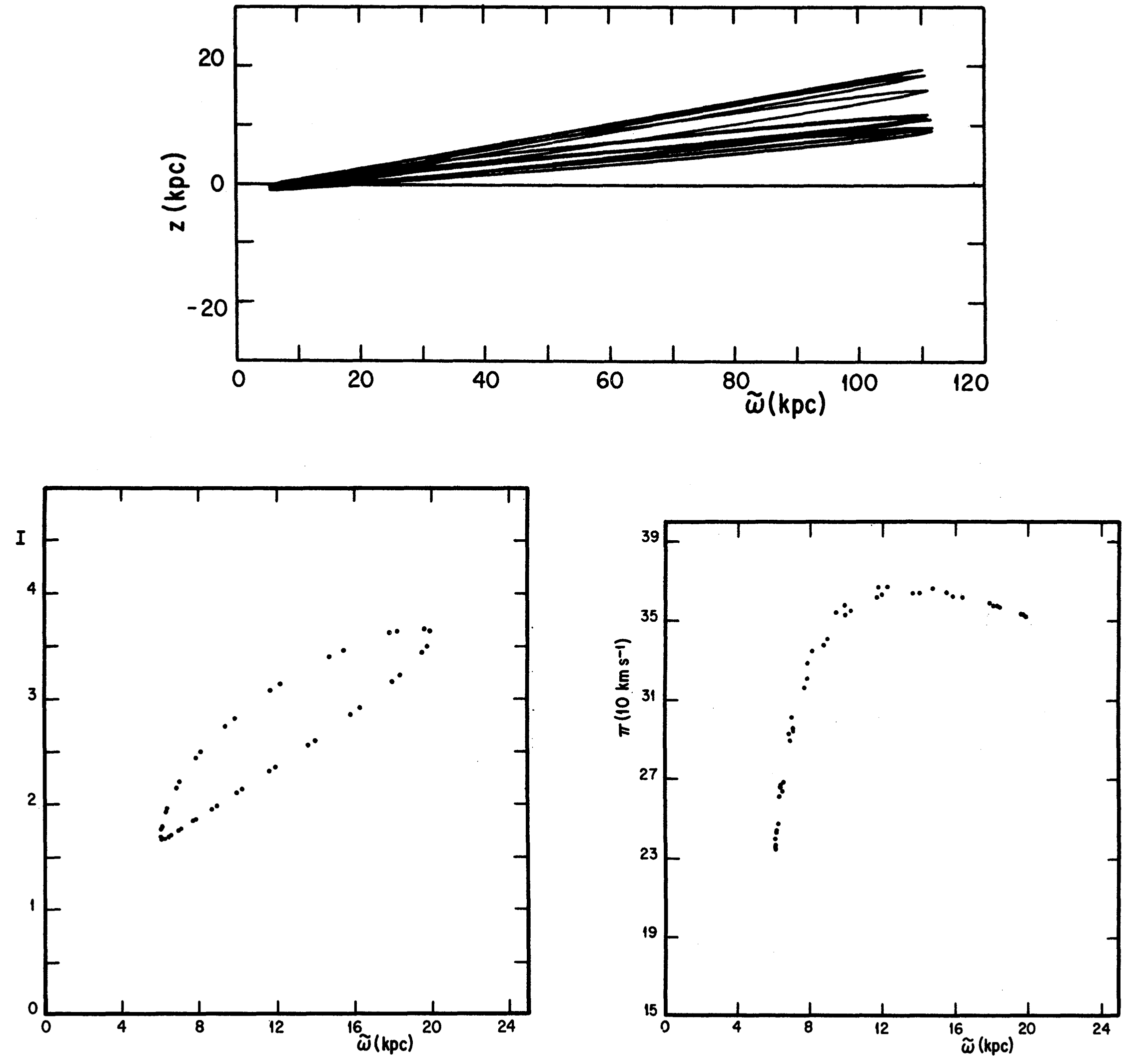

Fig. 3. (a) The meridional orbit of the companion, LDS 519B, run backwards in time for 1.6 × $10^{10}$ years. Figures 3(b) and 3(c) show the inclination diagram and the surface of section of this orbit. Note the similarity of the orbits of both components of this physical pair, LDS 519A and LDS 519B.

very sensitive to errors in the "initial" conditions, and that future, more accurate, determinations of the proper motion, the radial velocity or the distance of LDS 519 are not likely to drastically alter the characteristics of the galactic orbit here computed.

To evaluate the influence on the computed orbits of such effects as random encounters with molecular clouds and/or spiral arms, as well as to test their stability against such perturbations, the following experiment was performed: we subjected each star to velocity perturbations of random direction and of a magnitude $\Delta v = 0.78$ km $s^{-1}$ per million years whenever its distance from the galactic plane (its z-coordinate) became smaller than 500 pc. As shown by Wielen (1977), the orbital diffusion caused by such perturbations accurately accounts for the empirically determined increase with age of the stellar velocity dispersion. The perturbed orbits of both components were calculated backwards and forwards in time for 1.6 x $10^{10}$ years. They are shown in Figures 4 to 7. We note that the perturbed orbits are generally more symmetrical with respect to the galactic plane than the unperturbed ones; in fact, the perturbations seem to have the general effect of scattering the orbit out of the tube-like region and into the region of

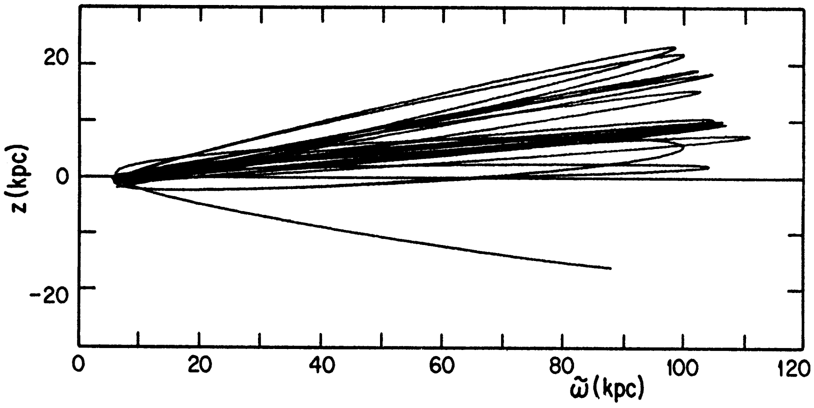

Fig. 4. The meridional orbit of the primary, LDS 519A, subjected to random perturbations during its passage through the galactic disk. The orbit was run backwards in time for 1.6 × $10^{10}$ years.

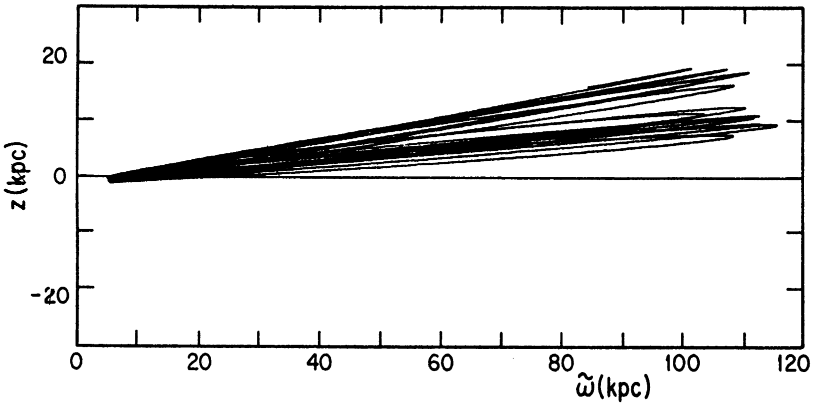

Fig. 5. The meridional orbit of the companion, LDS 519B, subjected to random perturbations during its passage through the galactic disk. The orbit was run backwards in time for 1.6 × $10^{10}$ years.

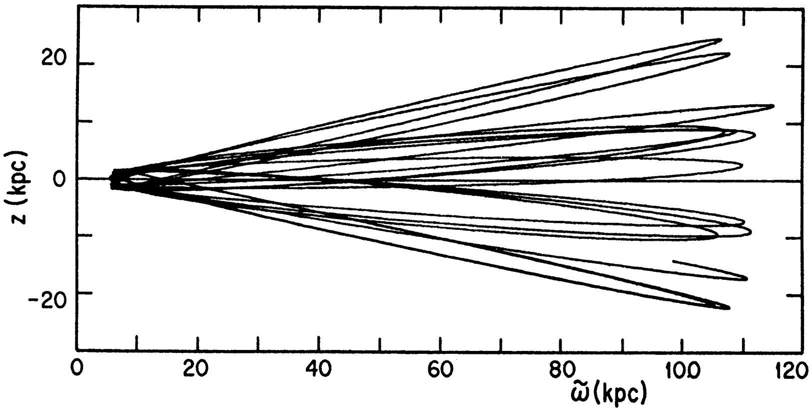

Fig. 6. The meridional perturbed orbit of LDS 519A, run forwards in time for 1.6 × $10^{10}$ years.

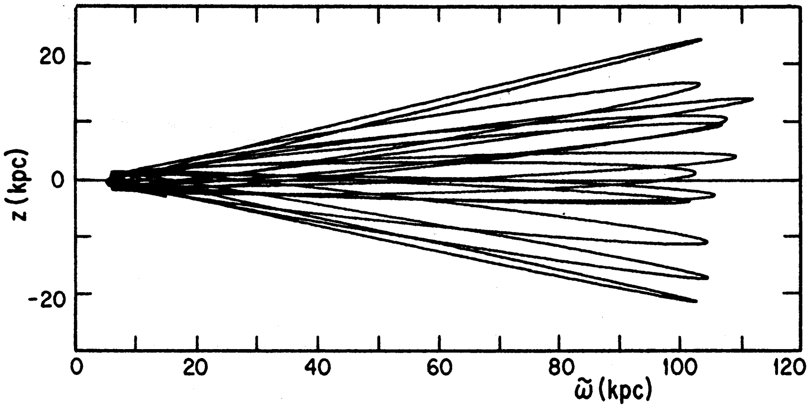

Fig. 7. The meridional perturbed orbit of LDS 519B, run forwards in time for 1.6 × $10^{10}$ years.

box-orbits; only the orbit of Figure 5 (which corresponds to LDS 519B run backwards in time) seems to preserve its tube-like character. However, the quantitative characteristics of all the perturbed orbits are not too different from the unperturbed ones. The radial distances and the heights above and below the plane reached by the stars become even larger than in the unperturbed case, *but even in a total time as large as* $t = 3.2 \times 10^{10}$ *years they do not escape.* These computations show that the maximum apogalactic distances reached by the perturbed orbits differ from those of the unperturbed ones by less than 10 percent.

## IV. DISCUSSION AND CONCLUSIONS

First, we have seen that the remarkable nature of LDS 519 is confirmed by its galactic orbit. We have shown that the general features of the orbit are not very sensitive to either errors in the observed data or to the perturbations likely to occur in the galactic disk. To be sure, the apogalactic distance reached by LDS 519 will vary according to the extent and the density of the halo. Current evidence points to a halo extending at least to 40-50 kpc and to a total galactic mass of nearly $10^{12}$ solar masses (see, among others, Hartwick and Sargent 1978; Frenk and White 1980; White and Frenk 1983; Lynden-Bell et al. 1983; Peterson 1985). Nevertheless, we can try to assess the effect of a smaller total galactic mass on the orbit of LDS 519; for this purpose, we have plotted in Figure 8 the escape velocity of objects in the solar vicinity as a function of different limiting radii for the halo (implying different total galactic masses). The escape velocities were calculated using our mass model, but they will be similar for any galactic mass distribution giving a gently falling rotation curve beyond the solar circle and flattening out at large distances at a value of about 205 km $s^{-1}$. From Figure

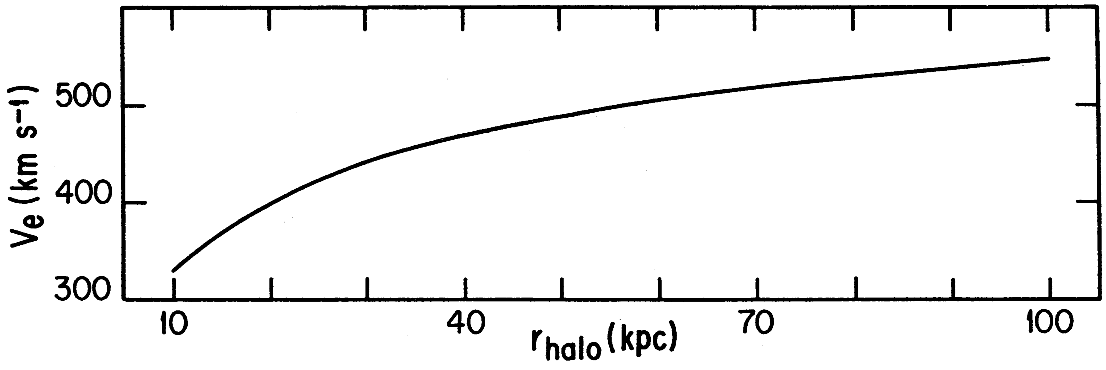

Fig. 8. The local escape velocity plotted as a function of the extent of the galactic halo. The galactocentric velocity of LDS 519 exceeds the local escape velocity if the halo extends to less than 38 kpc.

8 it follows that, if the halo were to extend to 38 kpc or less, then LDS 519 would not be bound, that is, its apogalactic distance would be infinite. Stated in equivalent terms, just in order to bind LDS 519 to the galaxy we need a galactic mass of at least 4.5 x $10^{11}$ solar masses. But assuming this minimum mass for the galaxy would mean that *galactic* objects such as LDS 519 would be able to reach apogalactic distances much larger than the total extent of the halo.

One way to fix the minimum extent of the galactic halo is to impose the consistency condition that it should be at least large enough to engulf the apogalactic distances of objects like LDS 519. With our adopted mass model, we can estimate that a halo extending to about 110 kpc (implying a total galactic mass of 1.15 x $10^{12}$ $M_{\odot}$) is just large enough to completely contain the orbit of LDS 519. Note that this distance exceeds that of the most remote Palomar-type clusters; is about twice the distance to the Magellanic Clouds and about 6 times the Holmberg radius of the Galaxy. If, as indicated by the luminosity function for nearby stars, we assume that one out of a thousand stars brighter than $M_V = 7$ in the solar vicinity ($r < 33$ pc) reaches such distances, we are led to the conclusion that in our galaxy the population of "normal" halo stars at R = 110 kpc is substantial.

Second, the very large velocity with which LDS 519 crosses the galactic disk indicates that it must have formed far away from the plane; in fact, it was most likely formed near apogalacticon, since at most other points of the orbit the velocity of the parent cloud would have been too large for it to survive supersonic collisions with other clouds. We have here an indication that the formation of the first and successive generations of stars in the galactic halo (as originally proposed by Eggen, Lynden-Bell and Sandage in 1962) took place as far out as 110 kpc.

An alternative explanation for the motion of LDS 519 would be that it acquired its high velocity as a result of random encounters with stars, molecular clouds, spiral arms and the like. However, this effect is not capable of transforming the typical velocities of disk stars in the solar neighborhood into anything like the space velocity of LDS 519 (Wielen 1977). A velocity change of the order of 250 km $s^{-1}$ is needed. A single close encounter with a massive object is more likely to accomplish such velocity changes. For instance, an encounter with a point mass of $10^9$ $M_{\odot}$ and with an impact parameter of about 100 pc would cause a change of velocity of the order needed. Smaller masses would require proportionately smaller impact parameters. Massive black holes could be invoked, but in order for an encounter as close as required to occur, their number density would have to be excessively large: their effect on the velocities of field stars would have been noticed long ago. On the other hand, single encounters with massive extended objects (like the Magellanic Clouds) do not produce large enough velocity changes. Apart from these difficulties, a single strong encounter will certainly disrupt such a weakly bound pair. For the same reason, it is very unlikely that the high velocity of LDS 519 was produced as a result of a supernova explosion. From these arguments, we conclude that the high velocity of LDS 519 is not due to a single encounter, nor to a series of small ones, nor to a supernova explosion, but rather it is a consequence of its remote place of birth and of the subsequent collapse of the galaxy as envisaged by Eggen, Lynden-Bell and Sandage (1962).

Third, the metallicities of LDS 519 A and B, as shown by their ultraviolet excesses (see Table 1) as well as by direct spectral analysis, are below normal, which is consistent with the remote birth place for these stars indicated by their galactic orbits.

Fourth, the duplicity of LDS is intriguing, as it is well known that high velocity stars tend *not* to be members of visual double or multiple systems. Abt (1983) has estimated that the proportion of visual binaries among high velocity stars is only about a fifth as large as that among low velocity stars. Furthermore, LDS 519 is a weakly bound pair with a projected separation of 10 000 AU, which has survived the cumulative disruptive effect of encounters with stars and molecular clouds for well over $10^{10}$ years. Very few binaries with such large separation are known; one of the best known examples is the Alpha Centauri system, which includes Proxima, our nearest stellar neighbor. However, the space velocity of this system is typical of the low-velocity stars, and it is younger than the Sun. The survival of LDS 519 as a wide binary can be understood in terms of its orbit: the high galactocentric velocity of this pair has caused it to spend most of its life in regions of low star and cloud density, and hence it has suffered a small number of encounters. When it does go through regions of high star and cloud density (close to the galactic plane) it does so at a very large velocity, and hence the energy exchanged is small, much smaller than it would be if the plane crossings occurred at a low velocity.

The qualitative similarity of the galactic orbit of LDS 519 to that of some globular clusters (Allen and Martos 1986b) supports the view that this binary is a vestige of an old, sparse globular cluster, long ago dissolved by the tidal action of the galactic bulge and/or by the fluctuating gravitational field resulting from its crossings of the galactic plane. We suggest that the simplest way to understand the origin of LDS 519 is as a binary formed in a poor, late-generation halo cluster (similar to the Palomar-type clusters) which, because of its highly eccentric orbit and low density, was destroyed by tidal effects or by gravitational shocks.

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## DISCUSSION

CARRASCO: Yo estoy de acuerdo en que pequeñas perturbaciones en el plano galáctico no podrían explicar la órbita, pero ¿cúal es el efecto de perturbaciones fuertes como las Nubes de Magallanes, la corriente Magallánica, etc.

POVEDA: Perturbaciones fuertes hubieran afectado una binaria tan débilmente ligada como es este caso; por lo tanto pensamos (dada la prolongada supervivencia de αDS519) que esta binaria no ha sufrido perturbaciones fuertes en el pasado.

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