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THE RADIAL VELOCITY AND VELOCITY DISPERSION OF THE REMOTE GLOBULAR CLUSTER PALOMAR 15: CONSTRAINTS ON THE MASS OF THE GALAXY[1]

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ABSTRACT

Radial velocities that are accurate to ± 2–3 km s^{-1} have been determined for four giants in the distant globular cluster Palomar 15. The dispersion in the observed velocities is so small that even with these data it is not possible to derive a reliable estimate of the actual internal velocity dispersion of the cluster. This suggests that its mass-to-light ratio is smaller than that of the dwarf spheroidal galaxies Draco and Ursa Minor, and is probably similar to that of other globular clusters. The weighted mean heliocentric velocity of the cluster is $+68.9 \pm 1.2$ km s^{-1}, and the galactocentric velocity of the cluster is +148 km s^{-1}. From the low velocity dispersion and large tidal radius, we infer a perigalactic distance ≥ 20 kpc. Although the cluster's present galactocentric distance is uncertain and its proper motion unknown, the most conservative orbital assumptions consistent with this perigalacticon imply that the total mass of the Galaxy is at least 2×10^{11} $M_\odot$. If the orbital assumptions were relaxed to a modest degree, or if preliminary determinations for other high-velocity clusters should prove correct, the lower limit for the Galactic mass could rise to at least 5×10^{11} $M_\odot$ from radial-velocity data alone.

Subject headings: clusters: globular — galaxies: The Galaxy — radial velocities

I. INTRODUCTION

Together with the dwarf spheroidal galaxies, globular clusters at large galactocentric distances are valuable sources of dynamical and chemical information about the remote halo of the Galaxy. Measurements of their systemic radial velocities, pioneered by Hartwick and Sargent (1978), provide one of the few probes of the mass distribution at large radii. Their internal velocity dispersions are currently the most promising way to check for dark matter in small stellar systems (Kormendy 1987). Their chemical abundances are vital to scenarios of the chemical enrichment of the halo.

We address the first two issues in this paper using new, accurate stellar radial velocities for individual stars in Pal 15. Our observations and the derivation of velocities are summarized in § II, and an upper limit to the velocity dispersion is discussed briefly in § III. The last two sections are concerned with the mass of the Galactic halo. In § IV, the systemic velocity of Pal 15 is established and a lower limit to its perigalacticon is inferred, based on its fragility. The assumption of a Galactic rotation curve constant to some radius R_{max} is invoked to predict the radial velocity of a fragile cluster on a parabolic orbit as a function of its distance and R_{max}. In § V, we summarize our results and reconsider the mass distribution of the Galaxy.

Increasingly accurate radial-velocity data is now available for individual stars in the remote satellites of the Galaxy (e.g., Peterson, Olszewski, and Aaronson 1986, hereafter POA; and Peterson and Foltz 1986). Based on new data, reassessments of the halo mass distribution have been made by Lynden-Bell, Cannon, and Godwin (1983), Peterson (1985, hereafter P85), and Olszewski, Peterson, and Aaronson (1986, hereafter OPA). All these papers argue for a substantial amount of mass beyond the solar radius. This is in accord with several other lines of evidence: the velocities of the globulars situated at intermediate radii, discussed by Frenk and White (1980); the high escape velocity of ≥ 500 km s^{-1} deduced for several individual stars in the solar neighborhood (Carney and Latham 1987; Carney, Latham, and Laird 1988); and the tendency of other spiral galaxies to show flat rotation curves to large galactocentric distances (Rubin *et al.* 1985). However, Little and Tremaine (1987, hereafter LT), applying a more sophisticated mathematical treatment of the satellite radial velocities, argue against more than a modest additional mass beyond ~ 20 kpc, the distance to which the rotation curve of the Galaxy has been determined to be flat (Blitz, Fich, and Stark 1982; Rohlfs *et al.* 1986). However, LT excluded Eridanus, Pal 14, and Pal 15 because of the large uncertainty in their systemic radial velocities. This exclusion significantly lowers the mass inferred for the Galaxy, as discussed in § V.

Although the systemic velocity of Pal 15 is now well determined (§ IV) its distance is uncertain. In this paper we treat the distance as unknown, derive the galactocentric radial velocity of a remote cluster on a parabolic orbit as a function of its present distance and perigalacticon, and evaluate the results for two specific estimates of the distance to Pal 15.

The standard distance estimate for Pal 15 comes from the tabulation of globular cluster parameters by Webbink (1985, hereafter W85). He deduced a heliocentric distance of 70 kpc using a reddening $E(B-V) = 0.12$ from the Burstein and Heiles (1982) H I maps and the horizontal-branch magnitude of $V = 20.2$ of Harris and van den Bergh (1984) coupled with $M_V(\text{HB}) = 0.6$. Taking the Sun to be 8.8 kpc from the center of

[1] Research based on observations obtained with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

the Galaxy, he found the galactocentric distance for the cluster to be 62 kpc. Based on star counts from various sources, he deduced core and tidal radii of 1.'35 and 5.'37, and thus r_c = 27.4 pc and r_t = 108.9 pc, and an absolute integrated visual magnitude $M_V = -5.4$. For the logarithm of the central mass density he lists −0.625, the lowest of any cluster. Assuming $M/L_V = 1.6$ (Illingworth 1976; Peterson and Latham 1986; Pryor *et al.* 1988), Webbink found a central velocity dispersion σ_i of 0.79 km s^{-1} and an escape velocity v_{sec} = 2.6 km s^{-1}.

Seitzer and Carney (1988, hereafter SC) argue for a much shorter distance, because the color of the blue horizontal branch in their color-magnitude diagram suggests a reddening of $E(B-V) = 0.45$. Albeit unlikely, this is certainly possible, since the cluster is seen in the direction of the galactic center at a galactic latitude of +24°. If $E(B-V) = 0.45$ is adopted, A_V becomes 1.44 instead of 0.38, and the heliocentric distance is lowered to 43 kpc and the galactocentric distance becomes 36 kpc. (Both distances are even smaller with SC's choice of 0.8 for the absolute visual magnitude of the blue horizontal branch.) At a heliocentric distance of 43 kpc, the core and tidal radii drop to 16.8 pc and 66.9 pc, respectively. Nonetheless, $M_V = -5.4$, because the change in distance is offset by the change in A_V. The log of the central mass density is increased to 0.0, still lower than all but five other cluster densities tabulated by W85. Finally, σ_i = 1.0 km s^{-1} and v_{esc} = 3.4 km s^{-1}.

II. SPECTRA AND VELOCITIES

Four stars in the field of Pal 15 were observed with the echelle spectrograph of the Multiple Mirror Telescope (MMT) on Mount Hopkins, Arizona, during the dark portions of 1986 July 24–29 UT. As described by Latham (1985), the echelle is used with an intensified Reticon detector plus image stacker with 1.''2 circular apertures, which results in a FWHM resolution of 9 km s^{-1} sampled across 6.5 pixels. The 50 Å spectral range was centered near 5190 Å.

The stars selected are the reddest and brightest of the giants in the SC color-magnitude diagram. The identifications and magnitudes from SC are given in Table 1. The stars' positions are from CCD measurements by SC normalized to SAO stars measured by R.C.P. using Don Wells's program ASTRO, and should be good to ~1''. Our velocities and their 1 σ uncertainties are included in the last columns along with references to previous radial-velocity measurements of the same stars. The agreement with OPA for SC3 is excellent. The P85 velocities have an estimated uncertainty of ±40 km s^{-1} (see OPA); this is consistent with the 1 σ deviation of a single measurement of the three stars in common with this work.

Conditions were excellent and the dark count of the detector was low, so that the stellar count rate exceeded that of the sky plus the dark for all Pal 15 giants except SC9. The total integration time listed in Table 1 was broken into segments of ~30 minutes, and a Th-A source was recorded for 90 s before and after each segment.

The standard data-reduction techniques for the Mount Hopkins echelle (Wyatt 1985) were employed here. These consist of dividing each exposure by that of an incandescent lamp obtained at the beginning or end of each night; combining all Th-A exposures acquired for an object to establish a fifth-order terrestrial dispersion solution (based on 30 lines, with an individual line position measured to ~0.02 Å); and applying this to the object. In these reductions, the continuum falloff introduced by vignetting and the echelle blaze function was not rectified, to maintain the local level of signal to noise. Also, no background subtraction was done, because this is dominated by the dark count rather than the sky (POA). The dark count is smoothly varying across the spectrum, and so it does not influence in a systematic way the position of the cross-correlation function peak.

Our results for the radial velocity and its theoretical uncertainty were derived from the standard cross-correlation analysis (Tonry and Davis 1979; Wyatt 1985). We used the extremely metal poor set of four templates obtained during the same run and employed for the determination of M15 velocities by Peterson, Seitzer, and Cudworth (1988). The same zero point was also adopted. The expected internal errors of our data were calculated from the relation $\sigma_t = 8.3/(1+R)$ km s^{-1}, where R is the ratio of the height of the correlation peak to typical noise fluctuations (Tonry and Davis 1979; Pryor, Latham, and Hazen 1988). According to POA, $R = 2.5$ is generally the value below which the wrong correlation peak may be chosen. The values of R are 3.2, 3.2, and 2.7 for SC3, SC4, and SC7, respectively. Although $R = 1.6$ for star SC9, we are confident that the proper peak was selected since the deduced velocity is very near those of the other three stars. This measurement was given half weight in deriving the cluster mean of +68.9 ± 1.2 km s^{-1}.

The reliability of our results may also be judged visually from Figures 1 and 2. Figure 1 shows the spectra of Pal 15 stars SC4 and SC7. Included for comparison is a high signal-to-noise spectrum of the M15 star K144 = II-75 (Küstner 1921; Arp 1955), obtained during the same run by Peterson *et al.*, who used it as a radial-velocity standard. Several of the strongest lines in its spectrum can also be discerned in the Pal 15 spectra, despite their very low number of counts. Figure 2 shows the cross-correlation functions of the two Pal 15 stars versus the M15 giant.

III. THE INTERNAL VELOCITY DISPERSION

With the current data, the internal dispersion σ_{int} of the cluster stars may be examined. The three more accurate velo-

TABLE 1

HELIOCENTRIC RADIAL VELOCITIES OF PALOMAR 15 GIANTS

Star	R.A. (1950)	Decl.	V	$B-V$	Exposure Time (minutes)	Radial Velocity (km s^{-1}) This Work	Other	Reference
4..........	16h57m17s.6	−00°28'27''	17.2	1.63	90	67.1 ± 2.0	+10.8	1
7..........	16 57 21.8	−00 27 58	17.4	1.63	85	68.0 ± 2.2	−3.9	1
3..........	16 57 17.8	−00 28 58	17.1	1.76	43	69.4 ± 2.0	+81.4	1
							+71.2	2
9..........	16 57 10.9	−00 28 04	17.8	1.52	96	74.2 ± 3.2	...	...

REFERENCES.—(1) P85. (2) OPA.

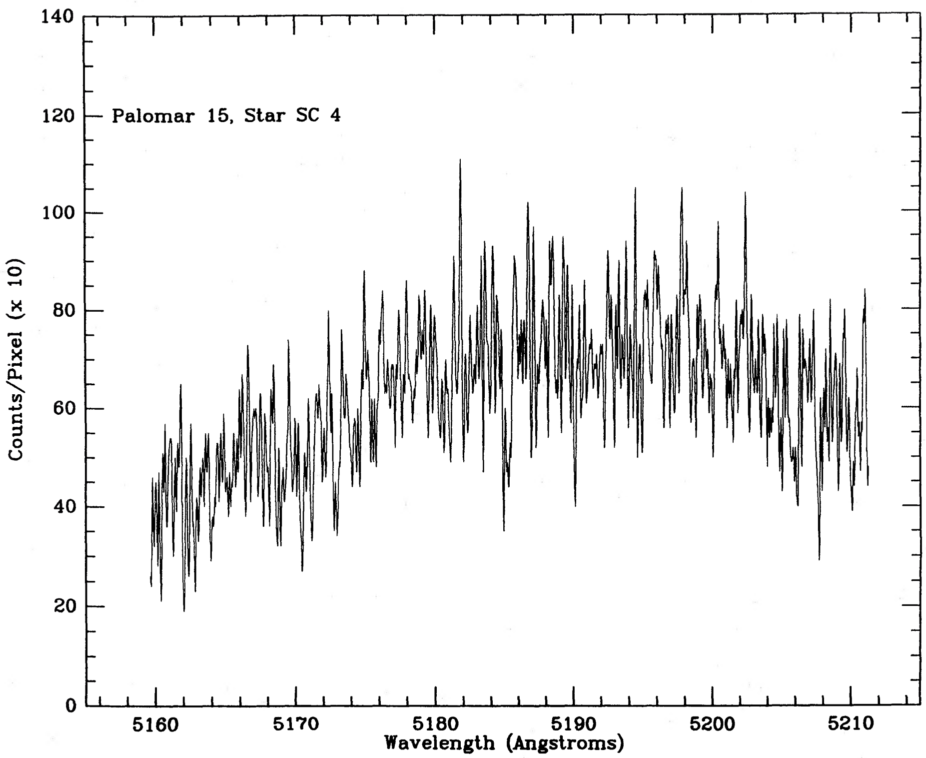

FIG. 1*a*

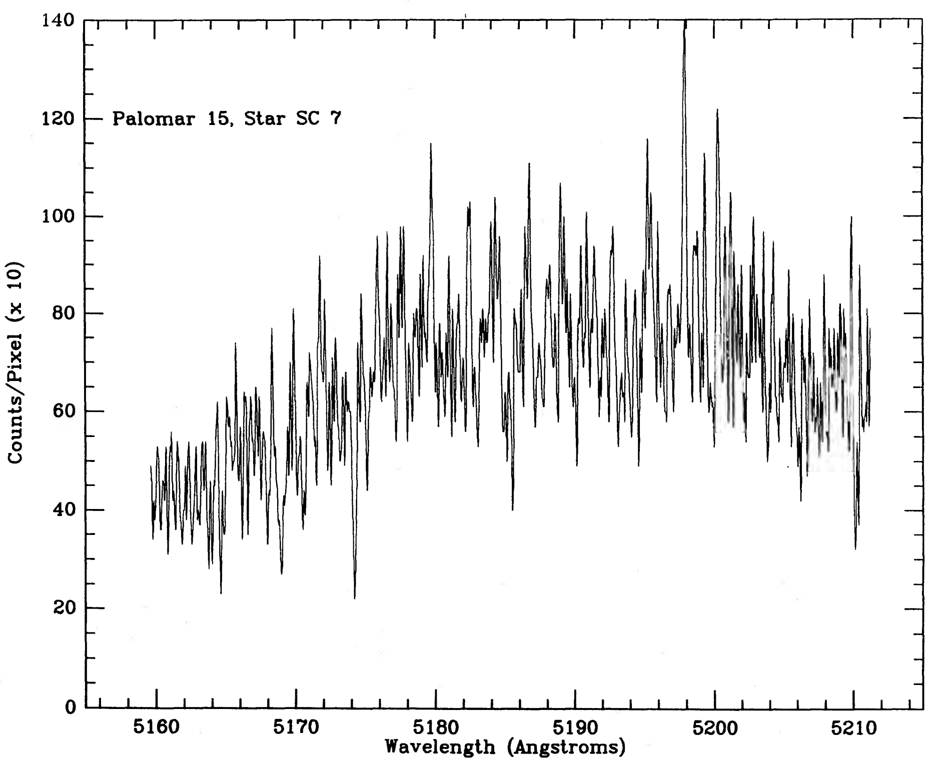

FIG. 1*b*

FIG. 1.—Spectra are plotted of two Pal 15 giants and one M15 giant for comparison. All spectra were smoothed five times (three for M15 K144) with a three-pixel triangle with weights 1/4, 1/2, 1/4. (*a*) Pal 15 SC4. (*b*) Pal 15 SC7. (*c*) M15 K144.

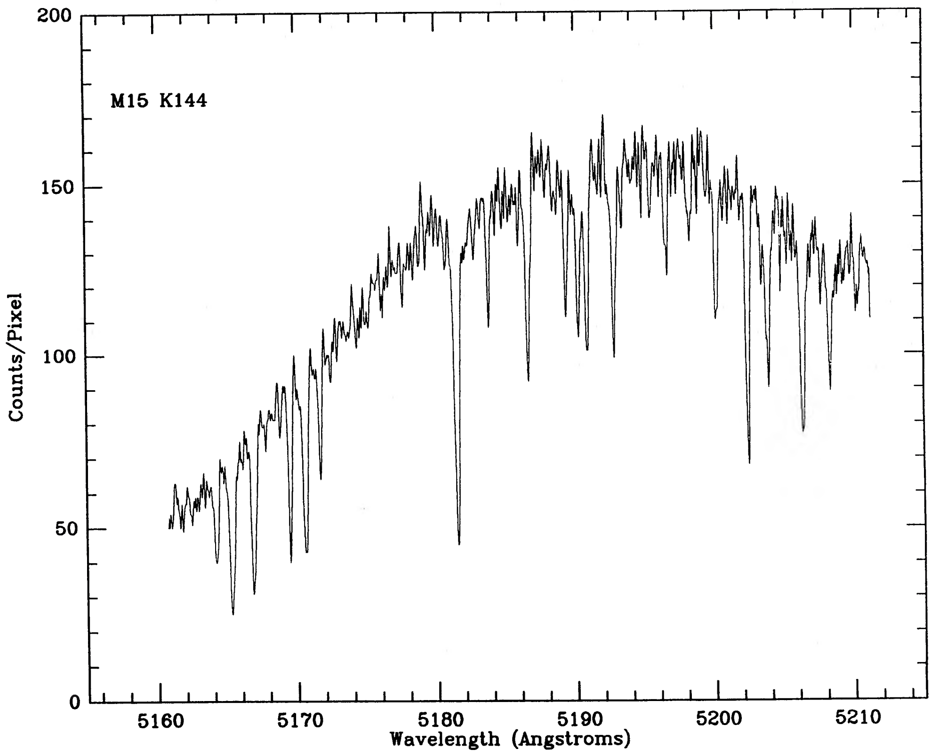

FIG. 1c

cities yield $\sigma_{obs} = 1.15$ km s^{-1}, a value smaller than the 2.1 km s^{-1} expected from measurement errors alone; the chances are less than one in five of obtaining a σ_{obs} this low even if $\sigma_{int} = 0$. The straight mean of all four velocities produces $\sigma_{obs} = 3.15$ km s^{-1}, from which $\sigma_{int} = 1.9$ km s^{-1} would be deduced if the measurements were equally accurate. We cannot rule out a true σ_{int} of 2 km s^{-1}, from which $M/L = 10$ would be inferred if the large distance to Pal 15 is adopted, while the shorter distance would give $M/L = 5$. However, it is unlikely that M/L is 6 times this, i.e. that the true $\sigma_{int} = 5$ km s^{-1}, for then the probability would be $\leq 30\%$ that $\sigma_{obs} \leq 4$ km s^{-1} if each velocity were known to ± 2.1 km s^{-1}.

Values of $M/L \approx 100$ have been found for the dwarf spheroidal galaxies Draco and Ursa Minor (Aaronson and Olszewski 1986, 1989), but for globular clusters not far from the Sun, $M/L \approx 2$ (Peterson and Latham 1986). Thus the data suggest that the mass-to-light ratio of Pal 15 is more consistent with that of other globular clusters than with Draco and Ursa Minor. This is in keeping with current structural ideas. Star counts indicate that most of the remote globular clusters are much less centrally concentrated than the globular clusters in the solar vicinity but are not as diffuse as Draco and Ursa Minor (Kormendy 1985). The central density of Pal 15 is at least an order of magnitude greater than that of Draco and Ursa Minor (W85). The probable similarity in M/L to other globular clusters adds weight to the ideas of Kormendy (1985) and Da Costa (1987) that globular clusters were formed differently from dwarf spheroidals.

IV. THE SPACE MOTION AND RADIAL VELOCITY OF A REMOTE CLUSTER ON A PARABOLIC ORBIT

The heliocentric velocity of Pal 15 is found from our weighted average to be $+68.9 \pm 1.2$ km s^{-1}. Reduced to the Galactic (i.e., nonrotating local) standard of rest by taking 8.5 kpc as the distance from the Sun to the galactic center, 220 km s^{-1} as the rotational velocity of the local standard of rest (LSR), and $(-9,12,7)$ km s^{-1} as the Sun's peculiar motion with respect to the LSR (P85, OPA, and LT), this becomes v(GSR) = $+147$ km s^{-1}. If indeed Pal 15 is truly remote, its v(GSR) is extreme; it is 50% larger than the largest velocity included in the samples of remote systems by LT.

On the other hand, if the revised galactocentric distance of 36 kpc discussed in § I is adopted, it is not obvious that this v(GSR) is very unusual. After all, NGC 5694 and NGC 7006 (at distances of 25 and 36 kpc, respectively) have v(GSR) = -238 and -166 km s^{-1} (see LT). However, the Pal 15 velocity is still significant, since its perigalacticon is limited by the fact that its central density is so small. In consequence, the latter clusters can approach the galactic center much more closely without being disrupted. Should Pal 15 be now at the short distance espoused by SC, however, we argue below that it must be very near perigalacticon. Thus its total space motion still must be large, because the tangential component of its velocity must be substantial. Owing to the problems in interpreting tidal radii (e.g., Innanen, Harris, and Webbink 1983; Seitzer 1983), this is currently the only additional constraint on the orbit of Pal 15 until a proper motion can be measured.

Let us estimate crudely the perigalactic distance R_P of Pal 15 as the lower limit of the present galactocentric distances R_{GC} of the globular clusters of similar structure. The estimates are the same whether tidal radii and escape velocity or central mass density are used as the criteria. According to W85, there are 16 clusters with tidal radii $r_t \geq 50$ pc and $v_{esc} \leq 10$ km s^{-1}. Ten have $R_{GC} \geq 38$ kpc while six have R_{GC} from 16 to 24 kpc. Alternatively, five clusters have a central density less than zero in the log, while six more have a density less than 10 times this.

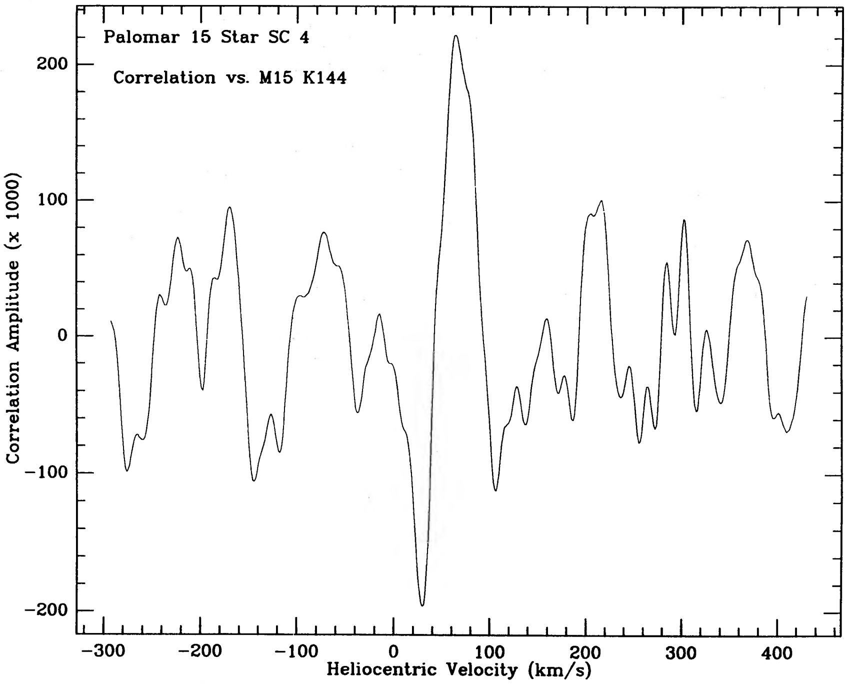

FIG. 2*a*

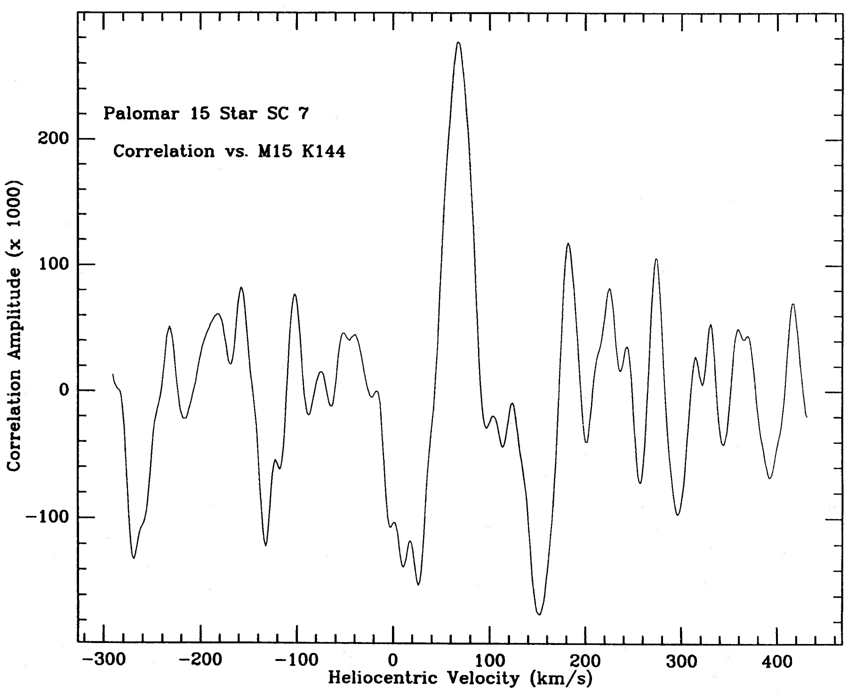

FIG. 2*b*

FIG. 2.—Correlation functions are shown for the two Pal 15 giants vs. the M15 giant. (*a*) Pal 15 SC4. (*b*) Pal 15 SC7.

Of the 11 total, seven have $R_{GC} \geq 40$ kpc while four have R_{GC} from 17 to 26 kpc. Thus R_P of Pal 15 is almost certainly at least 20 kpc.[2]

To see what this implies for the mass distribution of the Galaxy, we must make several assumptions. We take a simple model for the mass distribution of the Milky Way: all the mass is distributed smoothly within R_{max}, so that the rotation curve is flat to some distance R_{max}, beyond which it drops in Keplerian fashion. (Such models were also considered by Carney and Latham 1986 and LT, among many others.) We also assume the most loosely bound orbit, namely one with an eccentricity of unity. Beyond R_{max} this is a parabola. This permits the use of very simple analytical expressions.

First, take r as the present Galactocentric distance of a cluster, so the radial component of the velocity expressed in polar coordinates, v_r, is that seen from the galactic center. It is reasonable to let v_r represent v(GSR) since Pal 15 appears from the Sun to be rather close to the galactic center but lies well beyond it.

Next, recall that the total space velocity of a particle in a parabolic orbit is the local escape velocity $(2GM/r)^{1/2}$, i.e., $2^{1/2}$ times the local circular velocity. Because we have assumed an LSR velocity of 220 km s^{-1} and a rotation curve which is flat to R_{max}, we may take $v(R_{max}) = 2^{1/2} \times 220$ km $s^{-1} = 311$ km s^{-1}, no matter what R_{max} may be. Since the local circular velocity beyond R_{max} varies as $1/r^{1/2}$, the total space velocity beyond R_{max} becomes $(R_{max}/r)^{1/2} \times 311$ km s^{-1}.

Finally, adopt expressions for the relevant quantities from Thomas (1962, pp. 548–551). The orbit is given by $r = 2R_P/(1 - \cos\theta)$. The radial component of the velocity takes the simple form $v_r = v\cos\psi$, where the tangential angle ψ in Figure 11–21 of Thomas (1962) is found from $\tan\psi = r/(dr/d\theta) = -2R_P/(r\sin\theta)$. Ignoring the minor effect of the fact that for $R_P \leq R_{max}$, the true perigacticon distance is $\geq R_P$, we can calculate

$$v_r(R_P, R_{max}, r) = \cos\psi(R_{max}/r)^{1/2} \times 311 \text{ km s}^{-1}$$
$$= [(1 - R_P/r)(R_{max}/r)]^{1/2} \times 311 \text{ km s}^{-1} .$$

We choose an R_P, then pick an r. Once R_{max} is specified, v_r follows. The results of this calculation are shown in Table 2 for several choices of R_P, R_{max}, and r.

The calculations show that if Pal 15 is truly remote, with a galactocentric distance of 62 kpc (W85), its radial velocity implies that the rotation curve is flat to 20 kpc or more. This is still true for the revised distance of 36 kpc if $R_{max} \geq 20$ kpc, since a large tangential velocity component is unseen but present.

Moreover, the calculations should apply to any sparse, truly remote cluster, since the approximation $v_r \sim v$(GSR) is always valid at large r. The results in Table 2 could place important constraints on the mass of the Galaxy just from the radial velocity of a single such cluster, if its true orbit is nearly parabolic and v_r sufficiently large. Two candidates are discussed below.

[2] The bimodal distribution of cluster R_{GC}'s hints that two subsamples of clusters—for example, stripped near the galactic center and unstripped at large galactocentric distances—might be involved. If so, then $R_P = 40$ kpc might be a better guess for Pal 15, since its central density is low and its tidal radius is large.

TABLE 2

GALACTOCENTRIC RADIAL VELOCITIES[a] FOR PARABOLIC ORBITS

r[b]	$\cos\psi$	VALUE[b] OF R_{max}: 20	30	40
		$R_P = 20$ kpc		
30........	0.58	147	180	...
40........	0.71	156	191	220
60........	0.82	147	180	207
80........	0.87	135	166	191
		$R_P = 30$ kpc		
40........	0.50	110	135	156
60........	0.71	128	156	180
90........	0.82	120	147	169
		$R_P = 40$ kpc		
60........	0.58	104	127	147
80........	0.71	110	135	156

[a] In km s^{-1}.
[b] In kpc.

V. SUMMARY AND DISCUSSION: THE MASS OF THE OUTER GALAXY

We have established that the velocity dispersion of Pal 15 is low, implying a mass-to-light ratio probably consistent with globular clusters but not Draco and Ursa Minor, in accord with the ideas of Kormendy (1985) and Da Costa (1987) that globular clusters were formed differently from dwarf spheroidals. We find that its radial velocity with respect to the nonrotating local standard of rest is +148 km s^{-1}, a rather high value.

Although its distance from the Sun is uncertain because of possibly high reddening, its radial velocity still allows us to place significant limits on the mass outside the solar orbit because the cluster's fragility constrains how close it can approach the galactic center. From analytical considerations, we have shown that, if the Galactic rotation curve is postulated to be constant out to 20 kpc and to fall beyond, then the radial velocity of Pal 15 is barely consistent with extremely conservative assumptions for the cluster orbit (parabolic with a perigalactic distance of 20 kpc). From Table 2, it is evident that if the perigalactic distance is in fact larger, the radial velocity alone implies that the galactic rotation curve remains flat out to that perigalactic distance. For example, if R_P were shown to be 40 kpc, then R_{max} would be forced to at least 40 kpc, and a mass of 5×10^{11} $M_\odot$, or ~ 5 times the mass inside the LSR, would be implied.[3]

As we shall now discuss, our view is that current evidence does point toward such a mass for the Galaxy, rather than the 2×10^{11} $M_\odot$ preferred by LT. Partly this is a matter of taste: LT favor isotropic or predominantly radial orbits rather than the predominantly tangential ones preferred by Lynden-Bell *et al.* and OPA. Calculations of destruction rates of globulars, such as those of Aguilar, Hut, and Ostriker (1988), show that clusters on radial orbits are preferentially torn apart, and that the distribution of the eccentricities of the survivors is hard to infer because the initial distribution is unknown. Aguilar *et al.*

[3] Since these calculations are for the most loosely bound orbit, the mass implied for a particular choice of R_P is actually a lower limit.

consider the possibility that this distribution may have been preferentially radial, since distant field halo stars show a radial anisotropy. However, the argument of Aguilar *et al.* that the bulge population may be the remnants of disrupted clusters may also apply to the remote field halo stars; if so, their orbits are not representative of the initial cluster orbits. It would be worthwhile to perform calculations of destruction rates explicitly for remote clusters as their distances and velocity dispersions become established, to assess the likelihood of various choices of perigalactic distance.

A second difference between our point of view and that of LT is that LT excluded Eridanus, Pal 14, and Pal 15, because of the large uncertainty in their systemic radial velocities. Although the velocities of Eridanus and Pal 14 remain uncertain, we feel it is unwise to ignore them entirely. The velocities which do exist, due to P85, strongly suggest that their systemic velocities are high (see OPA). In neither case is the uncertainty in cluster velocity due to measurement errors of unknown but large size. The random errors estimated in Table 2 of P85 are ± 22 and ± 9 km s^{-1} for Eridanus and Pal 14, respectively; other P85 error estimates have been borne out by subsequent, more accurate work (POA and this paper). Instead, the uncertainty in the systemic velocity of each cluster arises from not knowing which stars are members. To us it seems unlikely that all four of the stars measured in Eridanus and all six in Pal 14 are interlopers. If any of the P85 stars are members, the GSR velocity of each cluster is high.

In Eridanus, for example, the two brightest stars in the P85 sample have heliocentric velocities of -17 and -25 ± 2 km s^{-1} (POA; Peterson and Foltz 1986). This converts to v(GSR) = -137 km s^{-1}, already a rather high value. However, the GSR velocity for the next brightest pair is higher still. These stars have P85 heliocentric velocities of -82 and -103 ± 22 km s^{-1}, corresponding to v(GSR) = -210 ± 16 km s^{-1}. While the zero-velocity stars may well be field stars, it is unlikely that the high-velocity stars are interlopers, since their velocities are similar, the field contamination at this magnitude is expected to be small (Da Costa 1985), and both stars fall in the middle of the giant branch in Da Costa's color-magnitude diagram. Thus the true GSR velocity of the cluster might be near -200 km s^{-1}.

Confirming this is important, for this GSR velocity alone would necessitate a Galaxy more massive than that preferred by LT. The W85 galactocentric distance of 85 kpc for Eridanus has been verified by Da Costa (1985), so this velocity combined with a very conservative orbit—parabolic with a formal R_P = 20 kpc—would imply that $R_{max} \geq 40$ kpc (Table 2), and thus $M_\odot \geq 5 \times 10^{11}$ $M_\odot$.

Even if the lower GSR velocities for Eridanus and Pal 14 are correct, a mass as low as 2×10^{11} $M_\odot$ is possible only if Eridanus, Pal 14, and Pal 15 have an average orbital eccentricity very near unity. If their orbits have even modest eccentricities, or if perigalactic distances are 40 kpc rather than 20 kpc, then the Galactic rotation curve must remain flat to 40 kpc or more, and the total mass of the Galaxy again must exceed 5×10^{11} $M_\odot$.

Clearly, reliable systemic radial velocities are urgently needed for Eridanus and Pal 14, for these may raise the lower limit to the mass of the outer galaxy. However, determining the proper motions of one or more remote systems is crucial to the definitive determination of the mass at large galactocentric distances.

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