GLOBULAR CLUSTERS AS TRACERS OF THE GALAXY MASS DISTRIBUTION

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This review will consist of two parts: (a) a brief description of a new method to determine V_o, the circular speed of the local standard of rest, and which, of course, plays a fundamental role in the mass distribution of the Galaxy, and (b) a review of the globular clusters as tracers of the mass distribution in the Galaxy.

1. A NEW ESTIMATE OF THE CIRCULAR SPEED V_o OF THE LOCAL STANDARD OF REST.

V_o is poorly known, with contemporary values ranging from 180 to 280 km/sec (Mihalas and Binney 1981). The consequent uncertainty in the mass distribution is highly unsatisfactory. The new method to estimate V_o is straightforward to explain, and, in principle, yields a relatively accurate result (Carlberg and Innanen, 1986). The Galaxy is believed to contain a nucleus with a substantial mass that manifests itself as a strong rise in the rotation curve inside 2 kpc, peaking at about 250 km/sec, at around 500 pc. Stars with very eccentric orbits that pass through the nuclear region generally cannot be confined to a flattened disk distribution; their orbits are chaotic, i.e., they do not have third "integrals", and consequently they spend most of their time in the halo. In a local sample of old disk stars, there will be accordingly an apparent deficiency of stars with low angular momentum, because they are in a much higher scale height distribution. The deficiency should be observed in galactocentric tangential velocities, as a gap centered on the circular velocity as reflected in the motion of the LSR. The value obtained in this way thus is independent of R_o or the mass model; it depends only on the presence of a gap. The expected size and velocity width of the gap has been calibrated with a new mass model. Using the compilations of Woolley et al. (1970), and Gliese (1969), evidence is presented that the expected deficiency of low angular momentum stars does exist in the local stars. The strength of the conclusion is limited by the size of the sample of appropriate intermediate population stars, i.e., those that are both in a strongly flattened distribution and possess significant numbers of members at low angular momentum.

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The available data favor a scale and model-free value of V_o in the range 225-245 km/sec with a most probable value of 235 km/sec. The implication of this result for the system of globular clusters in the Galaxy is that the latter system must rotate with a mean speed of 235-170 = 65 km/sec, with an estimated uncertainty of 25 km/sec. This value is in reasonable accord with the value of approximately 80 km/sec obtained by Huchra et al. (1982) for the M31 globular cluster system. It would be most useful to have similar radial velocity data for globular cluster systems in other nearby disk systems.

2. GLOBULAR CLUSTERS, TIDAL RADII AND THE MASS OF THE GALAXY

The theory for the tidal truncation of a satellite stellar system (i.e, a globular cluster) moving in the gravitational field of a much more massive galaxy rests on a theory dating back to the time of Roche. In one form, this theory states that, in order to survive tidal disruption, the mean density of the satellite system must exceed by some fixed ratio the mean density of the galaxy within the perigalactic circle of the satellite:

$$m/r^3 > kM/R^3 \qquad (1)$$

where
- m = mass of the globular cluster
- r = tidal radius of the globular cluster
- R = perigalactic distance of the globular cluster
- M = mass of the galaxy interior to R
- k = a constant, the appropriate value of which is somewhat controversial.

The hope is that knowledge of m, r, R and k will produce the galaxy mass inside R. The realization of this hope has proven elusive; a fairly complete discussion of the associated problems can be found in the review of Innanen, Harris and Webbink (1983) (hereafter IHW). What follows is a brief review of the problems associated with the use of Eq. (1).

(i) The first point to be noted is that the mass M varies as the ratio of the cubes of two linear distances, so that errors in the latter quantities produce masses which suffer triply. This is self evident but a point that nevertheless deserves repetition.

(ii) r is usually referred to as the "observed" value of the tidal radius of the cluster. It is not normally observed at all in the classical sense, but rather is an empirical extrapolation of the run of surface density of stars in the central parts of the cluster to a zero value which invariably is buried well out in the field of the galaxy. Most of the globular clusters in the Galaxy are rather round and there is reasonable accord in various estimates of this "observational" quantity for about 66 clusters (IHW). There are, however, some well known exceptions. Very discordant data exist for such clusters as NGC 362, NGC 1851, M 53 and M 3 and must be discarded. Although special scale plates may be required, Irwin and Trimble (1984) have demonstrated with M 55 that automated equipment can match the results of tedious, human star-counting work.

(iii) It is normal practice next to assume that the observational value of r in (ii) is equal to a tidal radius caused by the galaxy and which can be evaluated by a simple theory. This has turned out to be a significant oversimplification. It is clear that those clusters spending most of their time in shorter period in the inner part of the Galaxy suffer more vigorous tidal perturbations than the more remote outriders. Thus the casual application of the same value of "k" in Eq. (1) to all clusters may be unrealistic. A gross example is to try to apply Eq. (1) with the King (1962) value of $k = 3 + e$ (e is the eccentricity of the cluster orbit) to Jupiter's outer, direct satellite to measure the Sun's mass. Seitzer and Freeman (see Freeman and Norris, 1981) have advocated the use of the King formula, whereas Keenan (1981a,b) and IHW have favored larger values for k. Both viewpoints may well be based on inadequate physics and/or oversimplified numerical experiments. As is now well known, many globular clusters have at their centers gravitational "machines" which continuously populate their envelopes with stellar ejecta from their cores. The rate at which the galactic tide can prune this envelope and thereby eventually establish a nominal equilibrium tidal radius is not known. It is interesting to note that in the much softer tide of the LMC, the younger, bluer clusters have very elliptical shapes.

(iv) The mass of the cluster is estimated from its integrated luminosity through the assumption of a constant mass to luminosity ratio m/l. Although m/l(visual) = 1.7 is the most common value, there is some evidence (IHW) that it could be as high as 3 or 5. Such high values imply the existence of dark matter in globular clusters (Peebles, 1984).

(v) In order to relate the cluster's present galactocentric distance to the perigalactic distance, it is necessary to invoke certain orbit- averaging methods. These methods (IHW) give the "most probable" distance which can be considered to be the present distance. Of course this requires an a priori assumption of the kind of potential the cluster moves in. Analytic expressions are available for both Keplerian orbits and for orbits in a logarithmic potential (flat rotation curve). The outcome of this exercise favors the flat rotation model (IHW), but it is not at all clear that the rotation curve of the Galaxy inside R_o is flat.

A fair summary of the above list (i)-(v) is that the basic problem is not yet well enough posed in the physical sense to warrant detailed analysis. This was the basic, disappointing conclusion reached by IHW. Despite this weakness, the available data indicate that the orbits of the clusters are more commonly round than elongated.

To escape this conclusion, either the theoretical tidal radii are too small by a factor of 2, or the mass-luminosity ratio of the clusters is too small by a factor of 2 to 3, or a combination of both of these.

The data for the galactic globular cluster system produces reasonable statistics out to a galactocentric distance of approximately 20 kpc. Beyond that value there are very few clusters. IHW used R_0 = 8.5 kpc and V_0 = 236 km/sec. The latter value is fortunately essentially the same as the value advocated above. Consequently, one may still use with confidence their derived mass distribution

$$M(R) = M_0(R/R_0)^{1.27+0.18} \qquad (2)$$

where $M_\odot$ = 1.1 x 10^{11} solar masses
so that M(20) = 3.26 x 10^{11} solar masses.

The large step from 20 to 100 kpc must be accomplished by using the radial velocities of a dozen or so distant globular clusters and dwarf spheroidals and by assuming that the virial theorem may be applied, together with an additional assumption such as isotropy. Hartwick and Sargent (1978) first performed this analysis and obtained a value of 8 - 10 x 10^{11} solar masses inside R = 100 kpc. A reexamination of the problem using more recent radial velocities (Olszewski et al. 1986) has been performed by Tremaine (1986) who finds a mass of 2 - 4 x 10^{11} solar masses. This mass confirms a similar value obtained by Lynden-Bell (1983). Evidently the outcome depends strongly on the accuracy of the sparse data, as well as the assumption of isotropy. These lower values of the coronal mass imply that the galactic rotation curve must decline beyond R = 25 kpc. It may well be the case that some of the most useful information about the outer mass distribution in the Galaxy will come from studies of the kinematics of relatively nearby high-velocity stars, as can be seen from the work of Carney and Latham (1986; also this symposium).

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DISCUSSION

GRINDLAY: First, an additional comment for the last talk. When I said in response to Cudworth's remark about the M 22 proper motion not agreeing with an X-ray bow shock, I should have pointed out that in our paper we explicitly mentioned M 22 could be a doubtful case because of the more likely contamination by other extended X-ray sources (e.g., uncatalogued supernova remnants) near the galactic plane. Now my question: How did you actually do orbit averaging to derive R_p values?

INNANEN: This can be done analytically for both "Keplerian" and logarithmic potentials (i.e., flat rotation curve potentials). The details are in Innanen, Harris and Webbink, A.J. 88, 338, 1983).

CARNEY: The field stars are germane to determining the Galaxy's total mass, too. There are two results in particular, Hawkins (1983) claimed to find an RR Lyrae variable with V_{rad} = -465 km/sec at R_{gc} = 59 kpc. This immediately indicates a Galactic mass of 1.4 x $10^{12} M_\odot$, if the star is bound. Second, the survey Dave Latham and I have been doing has revealed a few dozen nearby stars with Galactic-frame velocities of over 400 km/sec, and what looks like a power law distribution extending to 550 km/sec. As you said, the implied total mass depends are V_o but it appears the Galaxy's mass exceeds that interior to the solar orbit by a factor of at least five.

INNANEN: I agree entirely that such extreme velocity stars provide a invaluable probe as test particles of the Galaxy potential. It would seem extremely unlikely that we should see even a single intergalactic "tramp" star in the solar neighborhood.

OSTRIKER: 1) Lee and I recently found that clusters may be larger by a factor of 1.5 times the nominal tidal radius due to relatively slow loss rate outside the tidal radius. 2) It would be interesting to combine your analysis with that of Tremaine (who used radial velocities). Then, the orbital anisotropy could be estimated rather than assumed. Have you considered combining the two approaches?

INNANEN: Not yet, but the idea is worth pursuing.

WHITE: Of the four clusters with "terrible tidal radii", the first two, NGC 362 and 1851, have fields contaminated by the SMC so background sky contributions are 1) variable and 2) uncertain. The other two, NGC 5024 and 5272 (M 53 and M 3, respectively) lie in the direction of the NGP; don't know what went wrong there.

INNANEN: Yes, some clusters are intrinsically very difficult, but it's still disappointing to not be able to include them.

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COHEN: What is the expected effect of the Magellanic Clouds on the dynamics of the outer clusters in our galaxy?

INNANEN: They undoubtedly play a role in the range 40 < R < 70 kpc with capture and exchange as one possibility. I have no quantitative data to offer.

CUDWORTH: Anyone in North America who may be considering a massive plate scanning project to re-derive tidal radii should contact Roberta Humphreys at Minnesota regarding use of the automated plate scanner. This machine is much faster than a PDS microdensitometer with slightly poorer photometric precision, which should be adequate for such a project.

ARMANDROFF: Since the Olszewski et al. study, Gary DaCosta and I have redetermined the velocity of Sculptor based on 16 K-giants. The value has increased from +20 km/s adopted by Olszewski et al. to +107 km/s. This increases their mass estimate by ~10%. The last word has probably not been said about the velocities of many of the outer halo systems.

PETERSON, R.: Since the Olszewski et al. paper appeared, I have remeasured the space velocity of Pal 15 with MMT echelle values for 4 stars. The resulting systematic galactocentric radial velocity is as large as the largest values tabulated there. If its distance is correct (cf. Seitzer and Carney), it implies substantial matter at large galactocentric distance.

CARNEY: Pat Seitzer and I have obtained a color-magnitude diagram for Palomar 15, and the cluster appears to be severely reddened. If so, its distance declines by a factor of about three, and so it becomes less interesting (at least for this issue).

OLSZEWSKI: I pointed out that detector technology has vastly improved the quality of velocities and distances of distant globular clusters. Secondly, I pointed out that we used Lynden Bell's analysis -- the assumption of isotropy requires some objects on radial orbits -- this is a problem given the fragility of many of the outer systems. Using Lynden Bell's favorite correction the quoted mass estimate from our paper goes up ~ a factor of 2. We need measured orbits. Finally, I'll bet that the velocity of Hawkin's RR Lyrae is wrong by at least 100 km/s.

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