VII

GALAXY FORMATION

DYNAMICS OF GLOBULAR CLUSTER SYSTEMS

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In the Milky Way, the globular clusters are all very old, and we are accustomed to think of them as the oldest objects in the Galaxy. The clusters cover a wide range of chemical abundance, from near solar down to about [Fe/H] $\simeq -2.3$. However there are field stars with abundances significantly lower than -2.3 (eg Bond, 1980); this implies that the clusters formed during the active phase of chemical enrichment, with cluster formation beginning at a time when the enrichment processes were already well under way.

We do not yet know what happened during this phase of chemical enrichment, nor do we know how or why the clusters formed. Knowledge of how the clusters move is essential for understanding this phase, because the cluster kinematics reflect the conditions at the time of their formation. Also, clusters are useful as probes of the underlying galactic potential, so any knowledge about their orbital properties is worth having.

I will now give a comparative review of the kinematical properties of the globular cluster systems in the Milky Way, M31, and the LMC. First, a warning: the dynamical properties of the cluster systems may be different from the properties of the underlying diffuse stellar component with which the clusters are usually identified. There are two direct indications of such a difference: (i) the different range in [Fe/H] for the Milky Way clusters and the halo field stars, mentioned above; (ii) in several elliptical galaxies, the (U-R) color of the diffuse light at a given radius is significantly redder than the mean color of the globular clusters at that radius (Strom et al, 1981, Forte et al, 1981).

I. THE GALAXY

Two procedures have been used to study the orbital properties of the globular cluster system in our Galaxy. The first is to use the cluster radial velocities. These velocities are not usually a strong constraint

E. Athanassoula (ed.), Internal Kinematics and Dynamics of Galaxies, 359–364.

on the orbital properties of an individual cluster, but they are very useful statistically. From the radial velocities of 66 clusters, Frenk and White (1980) showed that the cluster system has a slow rotational velocity of 60±26 km/s, and is kinematically isotropic, with a line of sight velocity dispersion of 117 km/s. Recently Norris has made an unpublished solar motion solution for the nearby halo field stars; his values for the mean rotational velocity and velocity dispersion for these field stars (in the appropriate abundance interval) are in excellent agreement with those derived by Frenk and White for the clusters. So, at this level at least, the clusters and the stars of the diffuse stellar halo appear to be fairly similar kinematically.

The second procedure is to use the tidal radii of the globular clusters. These tidal radii are set by the galactic tidal field at the cluster's perigalactic distance R(min). Seitzer and I (unpublished) have used the tidal radii to estimate R(min) for a sample of 48 clusters; we assumed that the Galaxy has a spherical flat rotation curve potential with V = 220 km/s. The ratio R(min)/R, where R is the present distance of the cluster from the galactic center, is a statistical estimator of the cluster's orbital eccentricity. It turns out that the <u>tidally</u> estimated distribution of orbital eccentricities is consistent with the <u>kinematical</u> isotropy derived by Frenk and White.

We looked also at the dependence of orbital eccentricity on [Fe/H]. For clusters with R > 8.5 kpc, there is a wide range of [Fe/H] at a given R, but there is no apparent abundance gradient in the [Fe/H]-R plane (Zinn 1980). However for these outer clusters there is a striking dependence of R(min) on [Fe/H] : all our clusters of intermediate [Fe/H] plunge in to small values of R(min) (2 to 3 kpc), while the metal weak clusters have a wide range of R(min) values (2 to 15 kpc). This means that the intermediate abundance clusters with R > 8.5 kpc are all in highly eccentric orbits, while the outer metal weak clusters have a wide range of orbital eccentricities. This dependence of orbital eccentricity on [Fe/H] for the outer clusters has also been detected in a study that we have made of their kinematics.

Why should the outer intermediate abundance clusters be in highly eccentric orbits with small values of R(min) ? It may be that these clusters formed in the inner enriched regions of the early galaxy, and were then flung out in the (roughly spherical) violent relaxation of the spheroidal component. The metal weak clusters, on the other hand, may have formed throughout the early galaxy (cf Zinn's 1980 discussion of the second parameter effect), and the orbits of those metal weak clusters which formed in the outer parts of the system would be relatively unaffected by the violent relaxation. Alternatively, we recall that the <u>net</u> rotation of the metal weak halo field stars in the solar neighborhood is low. If the intermediate abundance clusters formed from accumulated enriched material lost by evolving stars of the early halo, then we could expect their angular momenta to be low, and their orbital eccentricities to be correspondingly high.

II. M31

From van den Bergh (1969) and Huchra et al (1982), we now have a sample of about 60 globular clusters with abundance determinations and accurate radial velocities. This sample covers a wide range in abundance, from [Fe/H] > 0 to [Fe/H] = -2.2, and shows only a weak radial gradient in abundance. The radial velocities can be used to estimate the change of mean orbital eccentricity with abundance for these clusters.

The more metal rich clusters ([Fe/H] > -0.6) form a rapidly rotating subsystem, with maximum rotational velocity of about 200 km/s (the rotational velocity of the flat part of the HI rotation curve is about 235 km/s), and velocity dispersion of about 90 km/s. There seems little doubt that these metal rich clusters lie in a fairly disklike (and therefore dissipated) system. It is not yet clear whether the metal rich clusters in the Galaxy lie in a similar disklike distribution. The metal weaker clusters ([Fe/H] < -0.6) show little net rotation, and their line of sight velocity dispersion is again about 90 km/s. This is surprisingly low, because the velocity dispersion measured for the diffuse stellar bulge is about 180 km/s (Capaccioli 1979). This low value may result from selection effects in the sample. For example, if the cluster orbits are fairly eccentric, then the highest velocities will be observed for clusters near perigalacticon, and these innermost clusters are the ones most likely to be omitted from the sample (cf de Vaucouleurs and Buta 1978).

From a simple histogram of radial velocities, we can in principle estimate the eccentricity distribution of the cluster orbits (assuming again a spherical flat rotation curve potential). However the probable selection effects make this difficult to do reliably. It is much less difficult however to estimate whether subsamples of the clusters have different eccentricity distributions. Again it turns out that the intermediate abundance clusters (-0.7 > [Fe/H] > -1.2) are in orbits of significantly higher eccentricity than the metal weak clusters ([Fe/H] < -1.3), at the 92 percent confidence level.

To summarise this section: (i) the metal rich globular clusters in M31 form a rapidly rotating disklike system; (ii) the intermediate abundance clusters have orbits of significantly higher eccentricity than the metal weak clusters. This latter effect was found earlier for the galactic globular clusters, from their tidal radii and then verified from their kinematics. Its appearance again, in M31, from the cluster kinematics, increases our confidence in its reality and therefore in its importance for galaxy formation theory.

III. The LMC

In our Galaxy and probably also in M31, the globular clusters are all old. Cluster formation took place during the phase of significant chemical evolution and apparently ceased about 15 billion years ago.

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The situation in the LMC is quite different. The LMC contains globular clusters of all ages. The oldest are similar in age to the halo clusters of the Galaxy. The youngest are only about ten million years old but, in structure and mass, they are similar to the old globular clusters. See Freeman (1980) for a brief review of their properties. We should ask why globular cluster formation is going on now in the LMC but not in the Galaxy: the answer may help us to understand the physical conditions in the Galaxy at the time of globular cluster formation.

Illingworth Oemler and I (in press) have made a study of the kinematics of the LMC globular cluster system. Combining our radial velocity data with similar data from Hartwick and Cowley, and Searle and Smith (which they kindly allowed us to use before publication), gives a sample of 60 clusters with ages from 10^7 to 10^{10} years.

The younger clusters (ages $< 10^9$ years) lie in a rotating disk similar to the HI/HII disk. The apparent rotation amplitude for this young cluster disk is V(rot) = 37±5 km/s, its galactocentric systemic velocity V(sys) = 40±3 km/s, its kinematic major axis is in position angle $1^\circ \pm 5$, and the line of sight velocity dispersion about the rotation curve is 13 km/s. The older clusters (ages $> 10^9$ years and including the halo-type clusters) also lie in a disk system, with velocity dispersion of 14 km/s and V(rot) = 41±4 km/s. However this old cluster disk has V(sys) = 26±2 km/s and the kinematic major axis is in position angle $41^\circ \pm 5$, very significantly different from the values for the disk defined by the young clusters and the gas. We do not yet fully understand this situation. We suggest that the kinematics of the old clusters reflects the gravitational potential of the LMC, while the kinematics of the gas (and the young objects that have recently formed from it) may have been affected by the interaction of the LMC, SMC and the Galaxy. Whatever the explanation, it seems clear that even the oldest clusters of the LMC are confined to a disk with a typical z-scaleheight of only about 600 pc, and there is no evidence for a kinematic halo population among the globular clusters of the LMC.

V. CONCLUSION

This comparison of the orbital properties of the globular clusters in the Galaxy, M31 and the LMC gives some useful insight into the formation histories of the cluster systems. In our Galaxy and M31, cluster formation began early, at a time when the chemical abundance was low. Cluster formation continued through the epoch of active chemical enrichment, and the mean orbital eccentricity of the cluster orbits increased as the chemical abundance increased. Cluster formation persisted, at least in M31, to a time when a fairly metal rich disk had already formed. In the LMC, the history was quite different. Although the oldest clusters appear to be metal weak, it seems that cluster formation did not begin until the LMC had already settled to a disk, and clusters have continued to form up to the present time.

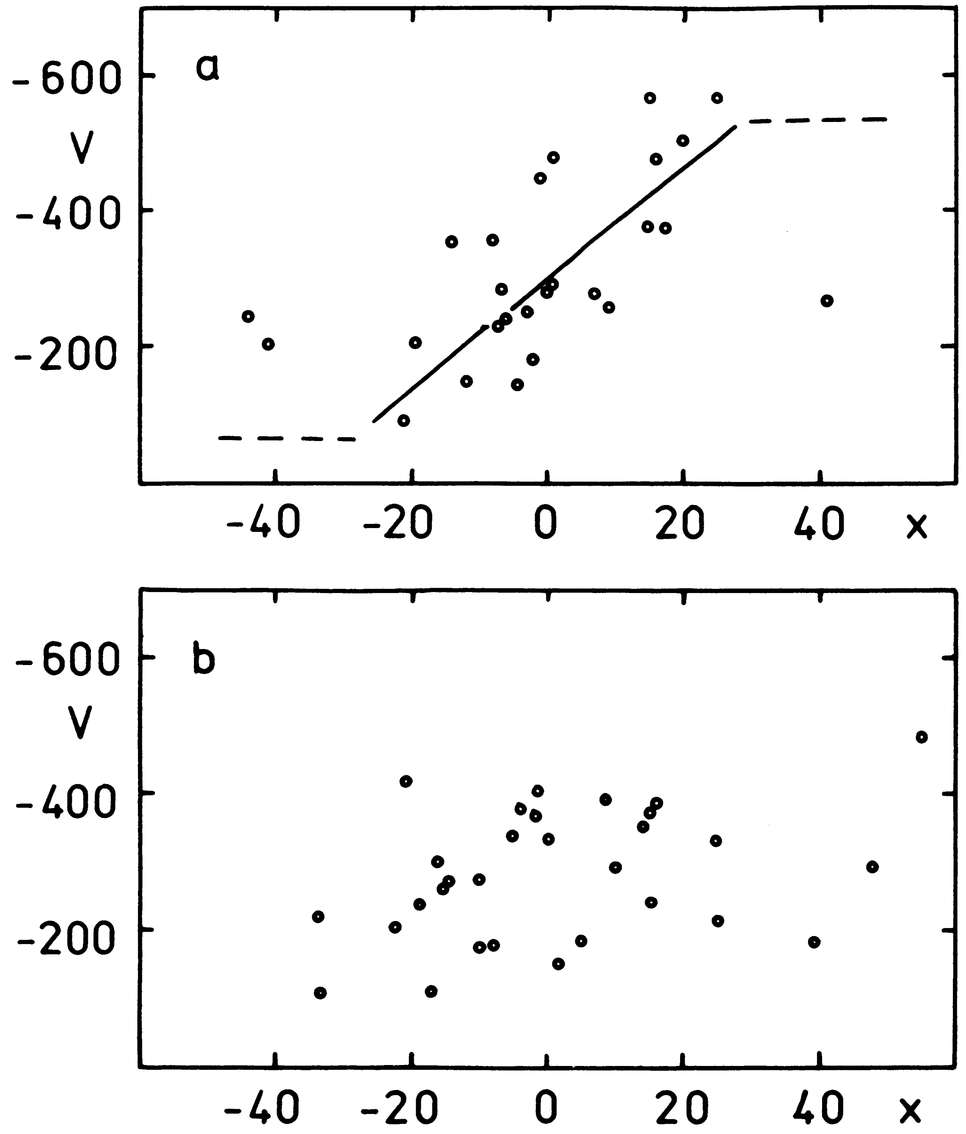

FIGURE 1

a) Rotation for the metal rich globular clusters ([Fe/H] > -0.6) in M31. V is the observed radial velocity (km/s) from Huchra et al (1982). X is the distance (arcmin) of the cluster from the minor axis of M31. The broken lines show the rotational velocity of the flat part of the HI rotation curve for M31. The unbroken line represents the mean rotation for these clusters. The rapid rotation of this subsystem is evident.

b) Similar diagram for the metal weak globular clusters ([Fe/H] < -0.6) in M31. These clusters show little net rotation, and their line of sight velocity dispersion is only about 90 km/s.

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REFERENCES

Bond, H.E. 1980. Ap.J. Suppl. 44, pp 517-533.
Capaccioli, M. 1979. Photometry, Kinematics and Dynamics of Galaxies , ed D.S. Evans (Department of Astronomy, University of Texas at Austin), pp 165-176.
de Vaucouleurs, G. and Buta, R. 1978. A.J. 83, pp 1383-1389.
Forte, J.C., Strom, S.E. and Strom, K.M. 1981. Ap.J. 245, L9-13.
Freeman, K.C. 1980. Star Clusters (IAU Symposium 85), ed J.E. Hesser, (Reidel, Dordrecht), pp 317-320.
Frenk, C.S. and White, S.D.M. 1980. M.N.R.A.S. 193, pp 295-311.
Huchra, J., Stauffer, J. and van Speybroeck, L. 1982. Preprint.
van den Bergh, S. 1969. Ap.J. Suppl. 19, pp 145-174.
Zinn, R. 1980. Ap.J. 241, pp 602-617.

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