SECTION II.2

THE STELLAR COMPONENT

Tuesday 31 May, 1020 - 1320

Chairman: M.W. Feast

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M.W. Feast pouring wine at conference dinner. With him, counter-clockwise around the table: G.P. Illingworth, R.H. Sanders, J.V. Feitzinger, N. Reid, C. Carignan, E. Sadler, Mme. Carignan LZ

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THE OLD POPULATION

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ABSTRACT

We review the kinematical and chemical properties of the old population of our Galaxy. Comparison is made with the properties of the old population in other disk galaxies.

INTRODUCTION

Disk galaxies like the Milky Way have two visible components, the disk and the spheroidal component. Both contain old stellar populations, which are the subject of this review. There is probably also an invisible component, which is probably old. For the Milky Way, this invisible component is discussed in the papers by Schmidt and Lynden-Bell. In some ways, this component is easier to study in other galaxies: see the paper by Carignan, for example.

THE SPHEROIDAL COMPONENT

In other galaxies, the spheroidal component (or bulge) appears as a single component. Its surface brightness distribution follows roughly the $R^{\frac{1}{4}}$-law, and it usually shows a radial color gradient, which is interpreted as an outward decrease in the mean metallicity. For the Galaxy, the nuclear bulge and the outer metal-weak halo are sometimes regarded as separate components. I suggest that it is more useful to consider the spheroidal component as a single dynamical system, with a chemical gradient. The inner more bound parts are relatively metal-rich, while the more energetic objects of the outer parts are more metal-weak.

Table 1 lists some of the gross properties of the Milky Way, for comparison with other galaxies. The estimates in this Table come from a compilation by de Vaucouleurs (1982: dV) from many sources. From these estimates, the Galaxy appears normal for its type. The absolute magnitudes

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TABLE 1

THE MILKY WAY

R_o	8.5 ± 0.5 kpc	sun-center distance
$V(R_o)$	220 ± 15 km s^{-1}	rotational velocity
$\sigma(0)$	130 ± 7 km s^{-1}	central bulge dispersion
$M_T(B)$	-20.2 ± 0.15	total integrated magnitude
$(B-V)_T$	0.53 ± 0.04	and color
$M_I(B)$	-18.2 ± 0.3	bulge integrated magnitude
$(B-V)_I$	0.65 ± 0.05	and color
$R_e(I)$	2.7 ± 0.3 kpc	bulge effective radius

of the disk and bulge are close to the average for Sbc systems (Simien and de Vaucouleurs, 1983), and the rotational velocity V_o of the disk and the central velocity dispersion $\sigma(0)$ of the bulge are close to those expected from the absolute magnitudes of these two components (dV; Kormendy and Illingworth 1982). We see that the spheroidal component is fairly small: it provides only about 15 percent of the Galaxy's integrated blue luminosity, and its effective (half-light) radius is only 2.7 kpc.

We now look at the kinematics of the spheroidal component in more detail. Table 2 gives the line-of-sight velocity dispersion for objects in the spheroidal component, at different distances from the galactic center. Sources for most of this data can be found in dV. Two of the measurements are recent. The value for the Sgr star clouds comes from direct measurement of the velocity dispersion from the integrated light of patches in these star clouds (de Vaucouleurs, Freeman and Wainscoat, to be published). The dispersion for giants at R = 25 kpc comes from Ratnatunga's study of giants of the outer halo (also to be published). We see from Table 2 that the spheroidal component is nearly isothermal out to about 60 kpc from the galactic center (> 20 effective radii).

From the work of Kormendy and Illingworth (1982), we would expect the inner parts of the spheroidal component to rotate; the maximum expected mean rotational velocity is about $0.7\sigma(0)$ = 90 km s^{-1}. This is roughly consistent with the kinematics of the planetary nebulae near the galactic center (Kalnajs and Webster, to be published). We also have an estimate of the rotational velocity of the spheroidal component near the sun, from observations of stars in the solar neighborhood. The sun is about 3 effective radii from the center, so we would expect the rotation to be small near the sun. Also, we would expect the spheroidal

Table 2

VELOCITY DISPERSION OF SPHEROIDAL COMPONENT
(one-component σ)

OBJECT	R(kpc)	σ(km s^{-1})
Planetary nebulae	< 1	130
OH/IR sources	near center	135
Long-period variables	" "	112
Late M stars	" "	113
Sgr star clouds	" "	120
RR Lyrae stars	2	125
" " "	8	140
Metal-weak giants, subdwarfs[1]	8	120
Globular clusters		120
Distant giants	25	124
Distant Palomar clusters, dwarf spheroidals[2]	60	125

[1]From Norris, unpublished

[2]From Hartwick and Sargent (1978)

component stars near the sun to be relatively metal-weak. This is nicely illustrated by Yoshii and Saio (1979). Their figure 1b shows the V-velocity of stars (i.e. the component in the direction of galactic rotation) against the ultraviolet excess δ(0.6). For the metal rich stars (low values of δ), fairly rapid rotation and low velocity dispersion are seen; these are the stars of the old disk. At δ(0.6) = 0.15, a fairly abrupt transition occurs, to a much hotter population with low mean rotation and lower mean metal abundance. This population is the spheroidal component. The value of the ultraviolet excess at which the transition from old disk to spheroidal component occurs near the sun corresponds to an abundance [Fe/H] = -0.6. Although many of the stars in the Yoshii-Saio sample were discovered kinematically, this does not appear to introduce a serious bias on the estimates of the mean rotational velocity for the spheroidal component stars in the solar neighborhood. A recent study by Norris (unpublished) of the kinematics of a large sample of spectroscopically selected metal-weak stars shows that their mean rotational velocity is very similar to that for the kinematically selected subdwarfs and also for the globular-cluster system (Frenk and White, 1981). All of these objects show a low mean rotational velocity of about 50 km s^{-1} (referred to a nonrotating frame).

The globular clusters and the metal-weak stars are both part of

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the spheroidal component. It is interesting to compare their chemical and kinematical properties. We have already seen that their mean rotational velocities are similar. There is an apparent difference in the distributions of [Fe/H] of the clusters and the stars. Field stars have been found with [Fe/H] less than -3, while the most metal-weak clusters have [Fe/H] ≃ -2.4. Is this difference significant ? Hartwick (1982) argues that it is probably statistical; both distributions are consistent with his chemical-evolution model, which has a zero initial metal abundance. (There are some well-known CN-abundance anomalies in globular-cluster stars, which are not so evident in the corresponding metal-weak field stars: see Kraft (1982). These anomalies are not yet fully understood. They may have to do with local processes in globular clusters, and are probably not relevant to this discussion).

Table 3 compares the velocity dispersion components for the nearby halo subdwarfs, halo giants, RR Lyrae stars and the globular-cluster system (from Hartwick, 1982). For the stars, the velocity dispersion is clearly anisotropic. On the other hand, Frenk and White's (1981) solution for the globular-cluster system produces an isotropic velocity dispersion. How seriously should we take this kinematical difference

TABLE 3

VELOCITY DISPERSIONS FOR GALACTIC HALO OBJECTS
($km\ s^{-1}$)

OBJECT	σ_R	σ_ϕ	σ_θ
Subdwarfs	178 ± 22	111 ± 39	106 ± 32
Giants	140 ± 16	108 ± 23	55 ± 31
RR Lyrae stars	145 ± 19	124 ± 22	71 ± 26
Globular clusters	118	118	118

(See Hartwick 1983 for references)

between the clusters and the halo field stars ? Fairly seriously, I believe: a quite independent analysis by Seitzer and Freeman (1982) showed that the distribution of orbital eccentricities for the clusters is consistent with an isotropic velocity distribution. They used the clusters' tidal radii to estimate the perigalactic distances R_{min}. The distribution of R_{min}/R for the clusters (where R is the present galactocentric distance) is a sensitive estimator of the distribution of orbital eccentricities. It is not yet clear that this kinematical difference between field stars and globular clusters was set up at the time of their formation. It is possible that the clusters originally had an anisotropic velocity dispersion also, and that the clusters in

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the more radial orbits have been destroyed subsequently by the galactic tidal field, as suggested to me by Ostriker and others.

The question of a radial abundance gradient in the spheroidal component is not yet settled. Among the globular clusters and RR Lyrae stars, the more metal-rich objects are found near the galactic center. Beyond about 8 kpc from the center, however, there is not much evidence for a radial gradient in their mean abundance. However there is a large spread in their abundance distributions in these outer regions; see Sandage (1981) for a summary. Some indirect evidence for a chemical gradient comes from the subdwarfs in the solar neighborhood. Eggen (1979) shows how the apogalactic distance for these subdwarfs increases with decreasing metal abundance. The more metal-rich subdwarfs mostly have small apogalactic distances, close to 10 kpc. Large apogalactic distances are seen only for the metal-weakest stars. This is consistent with a chemical gradient in the outer spheroidal component, but does not necessarily imply one. For example, it could be that the metal-weak stars with large apogalactic distances also have large orbital eccentricities (so that some are seen in the solar neighborhood), and that there are relatively metal-rich stars in low-eccentricity orbits far from the galactic center; these stars would of course not be seen near the sun.

The most direct way to settle the question of the abundance gradient in the outer spheroidal component is to study the chemical properties of halo stars that are now in these outer regions of the galaxy. Ratnatunga is now completing a program to discover halo giants spectroscopically, at distances of up to 40 kpc from the sun, to measure directly their chemical abundances and motions. This program provides a sample of distant halo objects, independent of the globular clusters and RR Lyrae stars. Preliminary results suggest that there is a significant gradient in the [Ca/H] values for these stars.

Finally we consider again the globular cluster system. We have seen so far that the system rotates slowly, has an apparently isotropic velocity distribution, and includes some relatively metal-rich clusters in the inner 8 kpc. The frequency distribution of abundances for the cluster system is clearly bimodal (see Freeman and Norris 1981, Figure 3). There is some evidence (see Zinn 1980 for example) that the clusters of the metal-richer mode belong to a disklike subsystem in the inner parts of the galaxy. Comparison with the cluster system of M31 supports the reality of this disklike system of metal-rich globular clusters. In M31, the metal-rich clusters lie in a rapidly rotating disk, within 10 kpc of the center. The metal-weaker clusters are in a slowly rotating system, as in the Milky Way (see Freeman 1983 for a review).

For $R > 8$ kpc in the Galaxy, we see only clusters of the metal-weaker mode: this mode includes clusters with $-1.2 > [Fe/H] > -2.3$. In this region of the Galaxy, there is a striking dependence of the orbital properties of the clusters on their abundance. Seitzer and Freeman (1982) showed (using the cluster tidal radii) that the more

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metal-rich of these clusters are all in highly elongated orbits; the more metal-poor clusters have orbits of all eccentricities. A similar effect is seen in M31, among the clusters of the slowly rotating subsystem mentioned above. From the frequency distribution of the cluster radial velocities, it appears that the metal-richer clusters of this subsystem are again in more elongated orbits than the metal weaker clusters.

In summary, the gross properties of the galactic spheroidal component are fairly much like those for similar spirals. The spheroidal component appears to be closely isothermal out to at least 60 kpc from the galactic center. Its abundance gradient is not yet clearly established. There are some interesting kinematical differences between the field stars and the globular clusters, and also between the metal-richer and metal-weaker clusters: these should be helpful for understanding the formation and evolution of the globular cluster system.

THE OLD DISK

The old disk is a major part of the old population of the galaxy. We will discuss some aspects of its structure here. First we should look at the structure of the disks of other galaxies. van der Kruit and Searle (vdKS: see van der Kruit and Searle, 1982, for references) have made surface photometry of several edge-on galaxies, and found a semi-empirical law to describe the luminosity volume-density distribution in their disks. This law has the form

$$\begin{aligned} L(R,z) &= L_o \exp(-R/h)\, \mathrm{sech}^2(z/z_o) & R < R_{max} \\ &= 0 & R > R_{max} \end{aligned}$$

where h and z_o are radial and z-lengthscales. For $z/z_o \gg 1$, $\mathrm{sech}^2(z/z_o) \sim \exp(-2z/z_o)$, so the usual exponential z-scaleheight is about $z_o/2$. This disk is exponential radially. In the z-direction, it has the structure of a locally isothermal sheet, if we assume that the mass density $\rho(R,z)$ also follows this semi-empirical law. The local z-velocity dispersion σ_z is then given by

$$\sigma_z^2 = z_o^2\, 2\pi G \rho(R,0).$$

This luminosity distribution L(R,z) is an excellent fit to the photometry of bulgeless disk galaxies. It is particularly interesting that the z-lengthscale z_o is independent of radius: this must be explained by theories for the heating of the stellar disk. Even from galaxy to galaxy, z_o does not change much. Table 4 gives values for some of the photometric parameters, for several galaxies studied by vdKS. V is the maximum observed rotational velocity, which varies from 95 to 255 km s^{-1} for this sample. Despite the range in V (and hence in total luminosity), z_o is relatively uniform at about 700 pc, which corresponds asymptotically to an exponential scaleheight of about 350 pc. In Table 4, $L_{o,J}$ is the value of L_o in the blue J-band, and the column headed "G" gives

TABLE 4

PHOTOMETRIC PARAMETERS FOR DISK GALAXIES

(from vdKS)

NGC	4244	5907	5023	4565	891	G
Type	Scd	Sc	Sc	Sb	Sb	Sbc
$L_{o,J}$ (10^{-2} $L_\odot$ pc^{-3})	3.2	3.3	4.1	4.5	2.4	4.0
h (kpc)	2.6	5.7	2.0	5.5	4.9	5.0
z_o (kpc)	0.6	0.8	0.5	0.8	1.0	0.7
h/z_o	4.5	6.9	4.3	7.0	5.0	7.1
R_{max}/h	5.3	3.4	3.9	4.5	4.3	4.4
V (km s^{-1})	115	210	95	255	225	220

estimates for our Galaxy: see vdKS for details.

For edge-on disk galaxies with even small bulges, the L(R,z) law above is no longer an excellent fit at all values of z. Near the galactic plane, the law fits well. However at larger z-heights, there is a clear excess of light above the $sech^2(z/z_o)$ law, even at large values of R, far from the central bulge. This excess of light appears similar to the thick disks identified by Burstein (1979) for edge-on SO galaxies. From the work of vdKS, this thick disk is seen in edge-on spirals only when a spheroidal component is also seen, so it is probably associated in some way with the spheroidal component. The thick disk could be the spheroidal component itself, responding to the flat potential of the disk (Jarvis and Freeman, preprint) or it could be an intermediate population that formed as the spheroid formed. There is some evidence from vdKS that the thick disk is slightly bluer (or more metal-weak) than the regular old disk. It seems important to understand what this thick disk is dynamically, and how it fits in to the galactic formation and disk heating pictures. The main point of this discussion here, however, is to warn us what to expect for the vertical structure of the Galaxy near the sun.

We turn now to the star-count data of Gilmore and Reid (1983) at the SGP. They measured I magnitudes and V-I colors for 12500 stars to I = 18 and, assuming that all these stars are mainsequence stars, they constructed the vertical number-density profile N(z). One interpretation of the structure seen in this N(z) profile is that it is the sum of two exponentials: one has a scaleheight of about 300 pc and dominates up to about z = 1 kpc, and the other has a scaleheight of about 1450 pc and contributes about 2 percent to the local density. Gilmore and Reid suggest that these two components may represent the regular old disk and the thick disk, respectively. The scaleheights would then be comparable to those seen in other galaxies. This particular analysis and interpretation remains contentious, however. Bahcall et al. (1983) argue that such a thick disk is inconsistent with other star-count data. It seems important now to resolve this question; if there is indeed a thick disk locally, then we have an excellent opportunity to study its chemical and kinematical properties directly. This would be a great help in understanding the nature of the thick disks seen in other disk galaxies.

Let us proceed, however, and assume that there are really two disklike components, with scaleheights of 300 and 1450 pc near the sun. The ratio of their z-velocity dispersions should then be about 2.2. If the velocity dispersion for the regular (300 pc) old disk is 20 km s^{-1}, then we would expect the 1450 pc component to have a velocity dispersion of about 45 km s^{-1}. Recently, Hartkopf and Yoss (1982) have published a chemical and kinematic survey of G and K stars at the galactic poles. While this survey does not claim to be complete, it makes some interesting points. The survey includes stars up to about 5 kpc from the galactic plane. Within a few hundred parsecs of the plane, all their stars have [Fe/H] > -0.5, and they identify this abundance range as normal (old disk ?). These normal-abundance stars are found not only near the plane, but also up to at least 5 kpc from the plane. They then look at the run of velocity dispersion with z for the normal-abundance ([Fe/H] > -0.5) stars and also for the metal-weaker stars ([Fe/H] < -0.5). The normal-abundance sample is almost isothermal up to about 3 kpc from the plane, with a velocity dispersion of 20 km s^{-1}. This is close to the usual old-disk value. The isothermal behaviour of this old disk is very interesting: recall the locally isothermal model of van der Kruit and Searle for the old disks of other spiral galaxies. The metal-weaker sample of Hartkopf and Yoss is also isothermal up to about 5 kpc, with a velocity dispersion of about 45 km s^{-1}. (Beyond 5 kpc the dispersion for this sample increases, probably due to a preponderance of population II giants in the sample at this distance.)

The close agreement of these two velocity dispersions (20 and 45 km s^{-1}) for the metal-rich and metal-weaker samples with the prediction at the beginning of the previous paragraph is interesting. It tempts us to identify the two isothermal subpopulations of Hartkopf and Yoss with the thin disk - thick disk structures of Gilmore and Reid and vdKS. The ratio of the velocity dispersions is in accord with the Gilmore and Reid scaleheights, and the chemical abundances correspond at least qualitatively to the vdKS color differences between thin and thick disks.

Finally we discuss briefly the presence of normal abundance stars far from the galactic plane. Hartkopf and Yoss found normal G and K giants up to 5 kpc from the plane. However there are also younger stars of normal abundance at similar heights. Rodgers (1971) studied 62 A stars at the SGP, with z-distances between about 1 and 4 kpc. About half of these have [Ca/H] > -0.5. Detailed spectrophotometry showed that they are not field horizontal-branch stars, but rather main sequence or slightly evolved stars, with ages of about 10^9 years. Hartkopf and Yoss propose a common origin for these high-z normal-abundance A and GK stars, perhaps resulting from an encounter with a third Magellanic system, as suggested by Rodgers et al. (1981). We recall, however, that the normal-abundance sample of GK stars has an isothermal velocity dispersion of about 20 km s^{-1} up to at least 3 kpc from the plane. At large z, this dispersion is of course determined by the normal-abundance high-z stars which we have just discussed. If their origin is different, as these authors suggest, then it would be worth understanding why their velocity dispersion is so similar to the dispersion of the other normal abundance GK stars near the galactic plane.

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DISCUSSION

J.P. Ostriker: The present isotropy of the globular-cluster velocity distribution (as compared to say the RR-Lyrae distribution) may indeed well be due to the destruction of clusters on eccentric orbits which pass near the centre of the Galaxy. In papers with Spitzer and Tremaine several years ago I found that massive clusters which come near to the centre would be dragged in by dynamical friction, and the low-mass (low-density) clusters destroyed by tidal shocks.

A.A. Stark: If a thick disk exists in our Galaxy, would it be as bright as the thick disks seen in other galaxies? Or are you implying that

there could be thick disks in all galaxies but they are just too faint to be seen?

Freeman: A thick disk makes no major contribution to the local density, only about 2%; but to the column density it is more like 10%.

Stark: Then if we looked from M31, could we see our thick disk?

Freeman: Yes, we would see our thick disk as we see it in other galaxies.

M.W. Feast: In your Table 2, the OH-IR stars have a velocity dispersion similar to that of the spheroidal component. However, I believe they are much more concentrated to the plane.

Freeman: An abstract by Habing and others (unpublished) claims that the OH-IR sources near the Galactic Centre are part of the disk population. But one may say the same for the planetaries. I just don't know. Maybe the disk has a velocity dispersion of about 100 km/s near the centre?

(Left to right) Clube, Van der Laan, Freeman and Hartwick during boat-trip. LZ

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