DYNAMICS OF STELLAR POPULATIONS IN GALACTIC DISKS

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ABSTRACT. We discuss observational data and dynamical considerations on the age dependence of the spatial distribution and of the velocities of stars in disk galaxies (thick disk, thin disk, spiral arms). We present new results on the age-velocity relation, on the heating of a galactic disk by massive black holes, and on theoretically predicted luminosity and colour profiles in edge-on galaxies.

1. Introduction

We shall concentrate in this paper on those effects in the spatial distribution and in the kinematics of stars which depend on the ages of the stars. This means that we consider the behaviour of different stellar generations born at various epochs. We do not discuss global phenomena such as galactic bars or warps.

It is an important question for our understanding of the evolution of galaxies which of the following processes are mainly reflected in the directly observed age dependence of the spatial distribution and kinematics of stars:

(a) the varying physical conditions in a galaxy at the epochs of formation of the different stellar generations,

(b) dynamical processes which occur after formation, during the lifetime of a stellar generation, or

(c) merger processes, during which (smaller) galaxies are captured by and dissolved in the (main) galaxy under consideration.

Probable answers to this question are different for various components of galaxies:

Halo/Bulge	:	(a) formation or (c) merging
Thick disk	:	(a) formation or (c) merging
Thin disk	:	(b) mainly dynamics
Spiral arms	:	(b) dynamics

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2. Thick Disk

The 'thick disk' is mainly seen in the density distribution of stars, derived in our Galaxy from star counts towards the galactic poles at distances z between 1 kpc and 4 kpc (Gilmore and Reid, 1983). The main question is whether the thick disk is really a distinct galactic component or a continuous transition between the halo and the thin disk. The relation between stellar metallicities and velocities, especially in the direction of galactic rotation, can also shed light on this problem (Gilmore et al., 1989; Carney et al., 1990).

It seems to us essentially unavoidable in any scenario in which the formation of a galaxy starts with the formation of a nearly round halo and proceeds later to the formation of a thin disk, to have a transitional phase in this process which leads to the formation of stars with spatial distributions, kinematics, and metallicities intermediate between the (extreme) halo and the (thin) disk. One would otherwise have to postulate an interruption of star formation between the halo and disk phases.

The thick disk cannot have been 'puffed up' from an old thin disk by normal dynamical processes in such a thin disk. It is already difficult to understand the dynamical formation of the old parts of the thin disk, with a scale height of about 0.5 kpc, from a thin gaseous disk.

The merging of one or more smaller galaxies with our Galaxy is a possible explanation for the formation of a thick disk. In such a scenario, the thick disk could be either the direct relict of the merged galaxy, dissolved and smoothly distributed in our Galaxy, or an old thin disk, formed before the merger event(s), could be 'puffed up' by the gravitational perturbations of the merging galaxy.

At present, no clear decision on the nature of the thick disk is possible. Our personal impression is that the thick disk is more likely the last phase of halo formation. If this conjecture is correct, the name 'thin halo' would be more appropriate than 'thick disk' for this phenomenon.

3. Thin Disk

The main observational facts on the age dependence of the spatial distribution and kinematics of stars in the (thin) disk of galaxies are:

(a) The age-velocity relation (AVR): the dispersion σ of the peculiar space velocities increases strongly with age τ.

(b) The scale height h_z in the z direction, perpendicular to the galactic plane, increases strongly with the age of a stellar generation. This is, of course, a dynamical consequence of (a).

(c) Young stars are mainly concentrated to (i.e. they are mainly born in) spiral arms; older stars are distributed smoothly over the whole disk (due to dynamical migration processes).

3.1. AGE-VELOCITY RELATION

The age-velocity relation for nearby stars has been derived by Wielen (1974, 1977) and Jahreiss and Wielen (1983), based mainly on the second Catalogue of Nearby

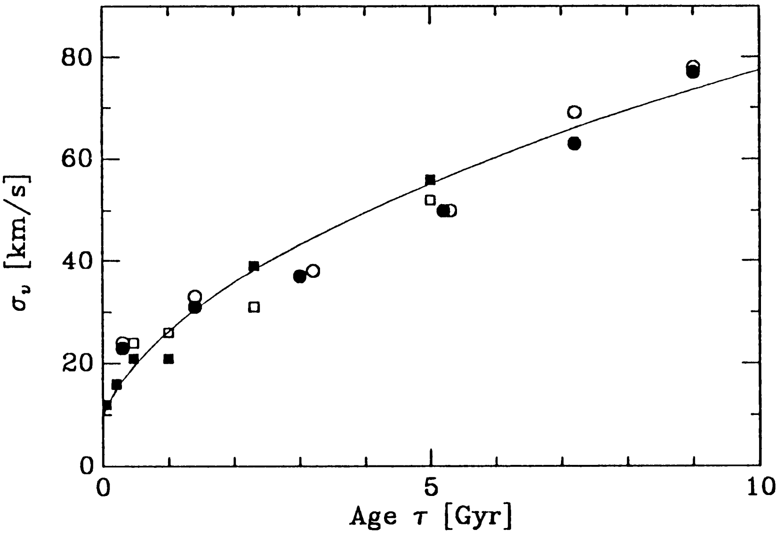

Fig. 1. Age-velocity relation for nearby stars. The total velocity dispersion σ_v is shown as a function of age τ. The data refer to a cylinder perpendicular to the galactic plane at the position of the sun. The filled symbols and the fitting line are taken from Wielen (1977), and are based on the 1969 version of the Catalogue of Nearby Stars. The open symbols are derived from the 1991 data of the Catalogue of Nearby Stars, for the same sample of stars. Circles refer to McCormick K and M dwarfs with measured Ca H and K emission intensities. Squares refer to cepheids or groups of main sequence stars.

Stars (Gliese, 1969). The main observational result of these studies was that the total velocity dispersion σ_v, derived from the three components $\sigma_U, \sigma_V, \sigma_W$ by $\sigma_v^2 = \sigma_U^2 + \sigma_V^2 + \sigma_W^2$, increases with the age τ roughly according to $\sigma_v^2 = \sigma_{v,0}^2 + C\tau$, i. e. $\sigma_v \propto \sqrt{\tau}$ for older stars. The total velocity disperson σ_v increases from $\sigma_{v,0} = 10$ km/s for the youngest stars up to about 80 km/s for the oldest disk stars. The velocity dispersion of the older stars is largely based on the McCormick K and M dwarfs with weak CaII H and K emission intensities. Since these dwarfs have been detected on objective-prism plates, they are free from kinematical selection effects.

Our results on the AVR were in good agreement with a study by Mayor (1974), based on evolved F stars. In recent years, however, a number of investigations (Carlberg et al., 1984; Knude et al., 1987; Stroemgren, 1987; Meusinger et al., 1991) have come to results which strongly deviate from ours. While the young part of the AVR is mostly in good agreement, many of these other studies propose an essentially flat AVR for older stars and smaller total velocity dispersions for the oldest disk stars, sometimes as low as about 40 km/s. The ages and distances of the evolved stars considered in these studies have been derived from photometric data based on the Stroemgren system.

We have confirmed our AVR by using the data from the latest (third) version of the Catalogue of Nearby Stars (Gliese and Jahreiss, in preparation). Figure 1 shows that the AVR based on the new data (1991) is in very good agreement with the AVR based on the old data (1969), although the distances of many stars have been significantly improved during this time. Especially the high velocity dispersions for the older stars are confirmed. Even if our ages for the oldest groups of stars were wrong, the high velocity dispersions of these groups would remain unexplained from the point of view of the other studies. It is also not conceivable that our oldest groups of stars are significantly contaminated by stars from the halo or even the thick disk, since our sample is located near $z = 0$, where the density of the halo and of the thick disk is very much smaller than that of the thin disk. It is also directly visible from the observed velocity distribution of our stars (e.g. Wielen, 1982) that the velocity dispersions are not governed by a few stars with extremely high space velocities.

The discrepancies in the AVRs cannot be explained, as already mentioned, by errors in the age determinations alone. If our AVR is correct, the other studies would have either underestimated the stellar distances (needed for calculating tangential velocities from proper motions, on the basis of the photometric data in the Stroemgren system), or the samples of stars used in these studies would not be representative of disk stars, essentially by avoiding old (and metal-weak) stars. The latter possibility, coupled with a large uncertainty in the ages of the 'older' stars, would explain both a flat AVR and smaller velocity dispersions for older stars found in these studies. Since we have confirmed our AVR using the most recent data on nearby late dwarfs, we shall continue to use this AVR as the observational basis for our dynamical considerations.

3.2. DIFFUSION MECHANISMS

The increase in the velocity dispersion of disk stars with increasing age is very probably due to the gravitational acceleration of stars after their birth by massive objects. Such an interpretation has been described by us in detail in a number of papers and reviews (Wielen, 1977; Fuchs and Wielen, 1987; Wielen and Fuchs 1983, 1985, 1988, 1989, 1990). Three different sources of the diffusion of stellar orbits have been proposed:

(a) Giant Molecular Clouds (GMCs): While GMCs have sufficiently high masses, of the order of 10^5 solar masses, their number at the distance of the sun from the galactic center is too small to explain the locally observed AVR. This has been shown by analytical means by Lacey (1984) and by numerical simulations by Dettbarn (ongoing Ph.D. work). GMCs are, however, highly effective in scattering stars. During such 'deflections', the stellar velocity changes its direction but not its amount. This process is probably important in transferring orbital energy from the motions parallel to the galactic plane into those perpendicular to it, and vice versa.

(b) Spiral arms, wavelets, and other instabilities in the galactic disk: Long-lived spiral density waves are not able to provide the required heating mechanism. Short-lived wavelets may, however, supply sufficient gravitational 'heating' for the galactic disk (e.g. Jenkins and Binney, 1990). GMCs are then required in addition to transfer energy from σ_U and σ_V into σ_W. It is, however, still uncertain whether or not

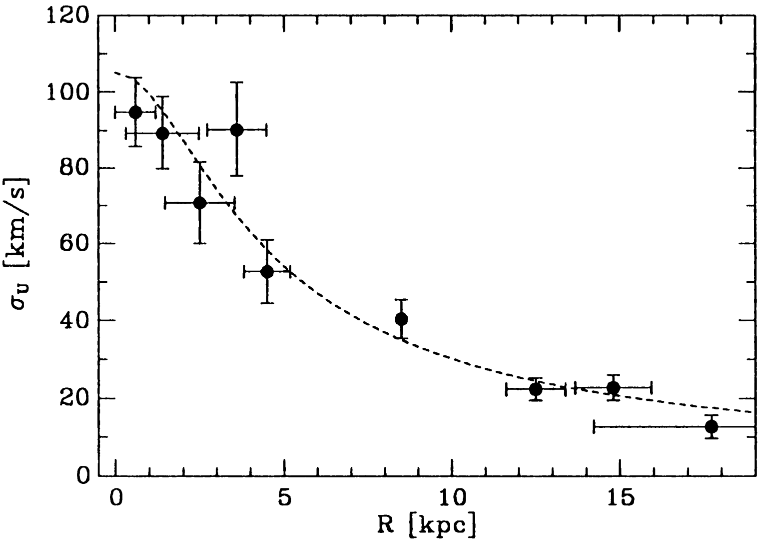

Fig. 2. The variation of the stellar velocity dispersion σ_U as a function of the distance R from the center of our Galaxy. Dots with error bars: Observational data from Lewis and Freeman (1989). Dashed curve: Theoretical prediction for $\sigma_U(R)$, based on the heating of the disk by massive black holes.

the lifetime and strength of a typical wavelet in our galactic disk is adequate to explain the observed AVR. One would need a rather noisy galactic disk ($\beta = 90$ in the terminology of Jenkins and Binney).

(c) Massive black holes (MBHs): Lacey and Ostriker (1985) and Ipser and Semenzato (1985) have proposed that massive black holes are the constituents of the dark coronae of galaxies and are responsible for the gravitational heating of galactic disks. MBHs explain nicely the observed property of the local AVR, namely $\sigma_v(\tau) \propto \sqrt{\tau}$. The individual mass of one typical MBH can be derived from the local AVR and from an estimate of the local mass density of the dark corona, based on the observed (flat) rotation curve. The result is about $3 \cdot 10^6$ solar masses, implying about 10^5 to 10^6 MBHs in the corona of our Galaxy. Heating of the galactic disk by MBHs would also explain the observed behaviour of the velocity dispersion $\sigma_U(R)$, in the radial direction as a function of the distance R from the galactic center, and a nearly constant thickness of the galactic disk, $h_z(R)$. This is shown in Figs. 2 and 3 which are based on formulae given by Wielen and Fuchs (1988), on a softened isothermal dark galactic corona with a density $\rho_{MBH} \propto (a^2 + R^2)^{-2}$ and $a = 3\,kpc$, a self-gravitating disk with a surface density $\mu_d(R) \propto exp(-h_R/R)$, and a flat rotation curve. MBHs would destroy globular clusters very effectively (Wielen 1985, 1987, 1988, 1991; Wielen and Fuchs, 1990). Hence the initial number of globular clusters in our Galaxy and in other galaxies would have been higher by a factor of about 10 or so compared to now, which does not seem impossible.

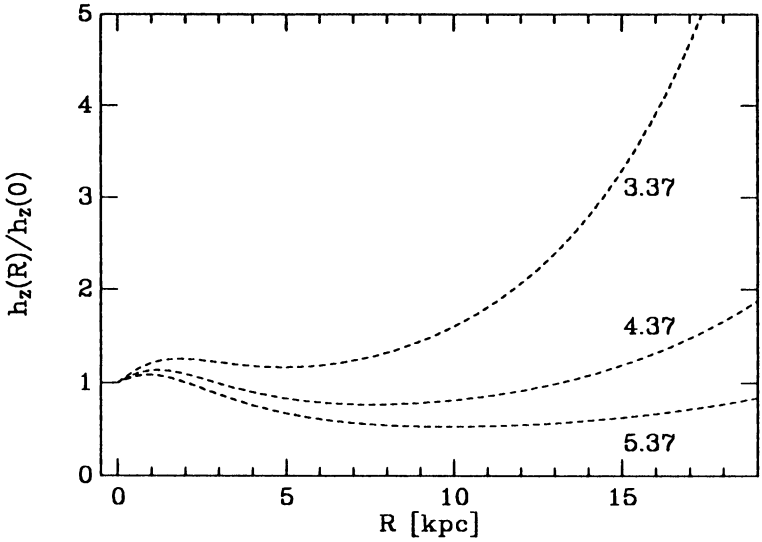

Fig. 3. Theoretical prediction for the scale height $h_z(R)$ in the z direction as a function of the distance R from the center of our Galaxy, based on the heating of the disk by massive black holes. The dashed curves show $h_z(R)/h_z(0)$ for various values of the exponential scale height h_R in the radial direction. The value of $h_R = 4.37$ *kpc*, derived by van der Kruit (1986), leads to a nearly constant value of h_z with respect to R, in fair agreement with observational data.

In summary, MBHs explain many observational results nicely, there are no firm observations which rule out the existence of MBHs, but, of course, MBHs are still quite speculative objects.

3.3. EDGE-ON GALAXIES

The increase in the perpendicular scale height, $h_z(\tau)$, with increasing age τ of a stellar generation is directly observed in the solar neighbourhood only. In other parts of our Galaxy and in external galaxies, no quantitative confirmation of this effect is available at present, although qualitative indications imply its general occurence in galactic disks. The most suitable candidates for studying the age-scale height-relation, $h_z(\tau)$, in external galaxies are those galaxies which are seen edge-on. Unfortunately, it is presently impossible to derive $h_z(\tau)$ from the distribution of individual objects of various ages, e.g. open clusters, in edge-on galaxies. At present, we can only investigate indirect consequences of $h_z(\tau)$, such as colour gradients in the z direction or the luminosity profile in the z direction. In both cases, the data are integrated over all ages τ (and also integrated along the line-of-sight).

The number of observational studies of the luminosity and colour profiles in edge-on galaxies with high photometric accuracy and high resolution in z is still rather limited but hopefully rapidly increasing due to the use of CCDs. A prototype

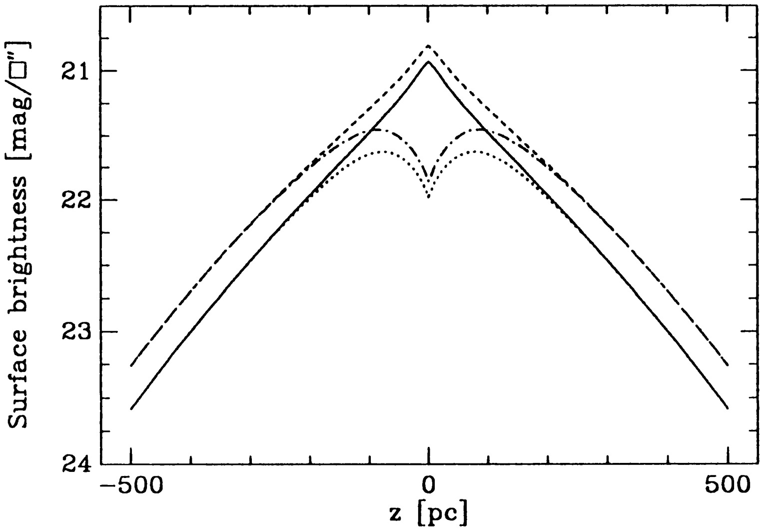

Fig. 4. Theoretical prediction for a luminosity profile in an edge-on galaxy, based on the diffusion theory of stellar orbits. The curves show the run of the surface brightness in the V filter (in magnitudes per unit area, with an arbitrary zero point) as a function of the height z above the galactic plane. Full curve: no dust, constant metallicity; dashed curve: no dust, age-dependent metallicity; dotted curve: with dust, constant metallicity; dash-dotted curve: with dust and age-dependent metallicity.

of such an investigation are the observations carried out by Wainscoat et al. (1989).

We have started to predict the luminosity and colour profiles in edge-on galaxies theoretically on the basis of a phenomenological theory of the diffusion of stellar orbits (G. Radons, ongoing Ph.D. work). In Figs. 4 and 5, we present some results which are based on a constant diffusion coefficient, on a constant star formation rate, and which would apply for an extragalactic observer who looks at our Galaxy edge-on and measures the profiles in the z direction at the solar distance ($R_\odot = 8.5\,kpc$).

Let us first neglect the absorbing effect of dust and the change of stellar metallicities with age. Then the luminosity profile, integrated over all ages, is extremely well-fitted by an exponential law. The colour profile shows the young blue stars at z = 0 and the redder colours of older stars at higher distances z. If we include an age-metallicity relation, the colour profile gets slightly flatter, because the older stars at higher z are not as red as before. The reddening by a dust layer with an exponential scale height of 50 pc has, however, a dramatic effect. The luminosity profile then shows a dip at z = 0, and the colour profile becomes flatter. If we add up all the effects, the colour profile varies only slightly with z, by about $0\overset{m}{.}1$. The exponential decline of the surface brightness is also strongly perturbed by dust absorption. In summary, our theoretical predictions for the luminosity and colour profiles in the z direction in edge-on galaxies seem to indicate that it should be

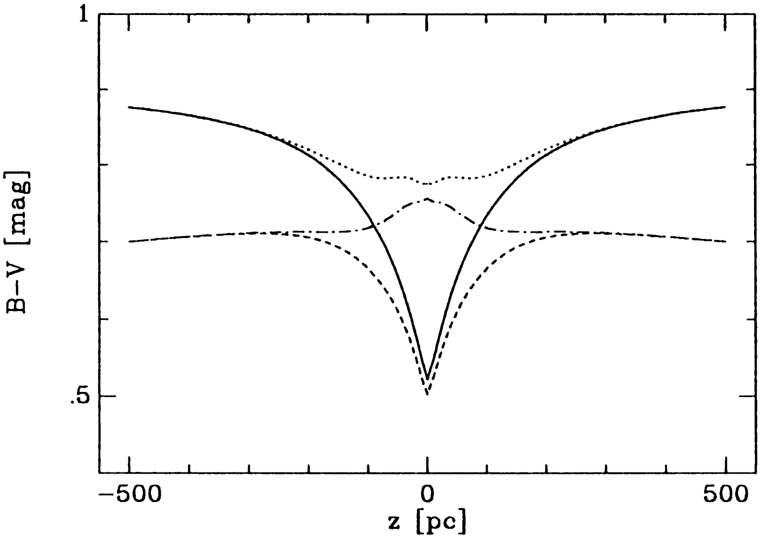

Fig. 5. Theoretical prediction for a colour profile in an edge-on galaxy, based on the diffusion theory of stellar orbits. The colour B-V (with a realistic zero point) is shown as a function of z. Full curve: no dust, constant metallicity; dashed curve: no dust, age-dependent metallicity; dotted curve: with dust, constant metallicity; dash-dotted curve: with dust and age-dependent metallicity.

rather difficult to disentangle the population effect $h_z(\tau)$ from other effects in the profiles of edge-on galaxies, especially from dust reddening. Nevertheless, it would be encouraging if the predicted luminosity and colour profiles can be brought into agreement with the observational data. This would strengthen our confidence that the increase of the scale height $h_z(\tau)$ with increasing age is a general phenomenon in disk galaxies, which may, of course, differ quantitatively from galaxy to galaxy, because of various heating mechanisms, star formation rates etc. .

4. Spiral Arms

There are two main dynamical processes which could cause spiral structure of grand design in a galactic disk: density waves and tidal interactions. Tidal interactions are certainly able to trigger spiral structure (e.g. Toomre and Toomre, 1972; Hearnquist, 1990). Such tidal arms are, however, transient phenomena. It is difficult to answer the question of whether or not long-living density waves occur in isolated galaxies because of some inherent instabilities of a galactic disk. C.C. Lin and his coworkers (Lin and Lowe, 1990; Bertin et al., 1989a,b) favour the existence of such quasi-stationary density waves, mainly on the basis of their analytical studies of the dynamics of galactic disks. Other theoreticians doubt the possibility of such global density waves, and are in favour of short-lived wavelets which are excited by 'swing amplification' (e.g. Toomre, 1981, 1990). Numerical simulations have difficulties in producing long-living density waves. Most simulations of isolated, non-barred galaxies produce wavelets and a spiral structure which varies rather rapidly in time (e.g. Sellwood, 1987). In barred galaxies or in galaxies with other oval distortions, it is much easier to excite spiral density waves of grand design by gravitational torques.

Whatever the dynamical cause of spiral structure is, it is very plausible that the higher density in the spiral arms, in contrast to the interarm region, triggers the formation of young stars in the spiral arms. In the frame-work of the density-wave theory, spiral shock-fronts are predicted in the gaseous interstellar medium or in the ensemble of interstellar clouds. Such shock fronts are normally also present in tidally-induced spiral arms. This triggering of star formation in spiral arms would explain the concentration of extremely young stars towards spiral arms. The initial dispersion of space velocities of young stars is already sufficient for the migration of these stars out of the spiral arms in which they were born. This produces an increase in the thickness of the spiral arms with increasing age of the stars used to define such arms. If the spiral structure is in addition a wave phenomenon, with a wave velocity different from that of the material, then the center of the spiral arm as defined by older stars, would also be displaced relative to that of newly born stars. This 'ageing' of spiral arms has been studied by numerical calculations of orbits of stars (e.g. Wielen 1978, 1979). The results are rather complicated, and it does not seem very promising to deduce the basic mechanism of the formation of spiral arms from a study of the spatial distributions and kinematics of stars of various ages.

References

Bertin, G., Lin, C.C., Lowe, S.A., Thurstans, R.P. (1989a), Astrophys.J. **338**, 78.

Bertin, G., Lin, C.C., Lowe, S.A., Thurstans, R.P. (1989b), Astrophys.J. **338**, 104.

Carlberg, R.G., Dawson, P.C., Hsu, T., Vandenberg, D.A. (1985), Astrophys.J. **294**, 674.

Carney, B.W., Latham, D.W., Laird, J.B. (1990), Astron.J. **99**, 572.

Fuchs, B., Wielen, R. (1987), in The Galaxy, G. Gilmore and B. Carswell (eds.), D. Reidel Publ.Comp., Dordrecht, p.375.

Gilmore, G., Reid, N. (1983), Mon.Not.R.Astron.Soc. **202**, 1025.

Gilmore, G., Wyse, R.F.G. Kuijken, K. (1989), Annual Rev.Astron.Astrophys. **27**, 555.

Gliese, W. (1969), Veroeff.Astron. Rechen-Inst.Heidelberg No. 22.

Hearnquist, L. (1990), in Dynamics and Interactions of Galaxies, R. Wielen (ed.), Springer-Verlag, Berlin, p. 108.

Ipser, J.R., Semenzato, R. (1985), Astron.Astrophys. **149**, 408.

Jahreiss, H., Wielen, R. (1983), in IAU-Colloquium No. 76, The Nearby Stars and the Stellar Luminosity Function, A.G.D. Philip and A.R. Upgren (eds.), L. Davis Press, Schenectady, New York, p. 277.

Jenkins, A., Binney, J. (1990), Mon.Not.R.Astron.Soc. **245**, 305.

Knude, J., Schnedler Nielsen, H., Winther, M. (1987), Astron.Astrophys. **179**, 115.

Lacey, C.G. (1984), Mon.Not.R.Astron.Soc. **208**, 687.

Lacey, C.G. Ostriker, J.P. (1985), Astrophys.J. **299**, 633.

Lewis, J.R., Freeman, K.C. (1989), Astron.J. **97**, 139.

Lin, C.C., Lowe, S.A. (1990), in Galactic Models, Proceedings of the 4. Florida Workshop on Nonlinear Dynamics, J.R. Buchler, S.T. Gottesman, J.H. Hunter (eds.), Ann. New York Acad.Sci., Vol. 596, p. 80.

Mayor, M. (1974), Astron.Astrophys. **32**, 321.

Meusinger, H., Reimann, H.-G., Stecklum, B. (1991), Astron.Astrophys. **245**, 57.

Sellwood, J.A. (1987), in Proceedings of the Tenth Europ. Regional Astron. Meeting of the IAU, Vol. 4, J. Palous (ed.), Publ.Astron.Inst.Czech.Acad.Sci., No. 69, p. 249.

Stroemgren, B. (1987), in The Galaxy, G. Gilmore and B. Carswell (eds.), D. Reidel Publ.Comp., Dordrecht, p. 229.

Toomre, A. (1981), in The Structure and Evolution of Normal Galaxies, S.M. Fall and D. Lynden-Bell (eds.) Cambridge Univ. Press, Cambridge (UK), 1981, p. 111.

Toomre, A. (1990), in Dynamics and Interactions of Galaxies, R. Wielen (ed.), Springer-Verlag, Berlin, p. 292.

Toomre, A., Toomre, J. (1972), Astrophys.J. **178**, 623.

van der Kruit, P.C. (1986), Astron.Astrophys. **157**, 230.

Wainscoat, R.J., Freeman, K.C., Hyland, A.R. (1989), Astrophys. J. **337**, 163.

Wielen, R. (1974), Highlights of Astronomy **3**, 395.

Wielen, R. (1977), Astron.Astrophys.**60**, 263.

Wielen, R. (1978), in IAU Symposium No. 77, Structure and Properties of Nearby Galaxies, E.M. Berkhuijsen and R. Wielebinski (eds.), D. Reidel Publ.Comp., Dordrecht, p. 93.

Wielen, R. (1979), in IAU Symposium No. 84, The Large-Scale Characteristics of the Galaxy, W.B. Burton (ed.), D. Reidel Publ.Comp., Dordrecht, p. 133.

Wielen, R. (1982), Kinematics and Dynamics of the Galaxy, in Landolt-Boernstein, Group VI, Vol. 2, Subvol.2c, Chapter 8.4, H.H. Voigt and K. Schaifers (eds.), Springer-Verlag, Berlin, p. 208.

Wielen, R. (1985), in IAU Symposium No. 113, Dynamics of Star Clusters, J. Goodmann and P. Hut (eds.), D. Reidel Publ.Comp., Dordrecht, p. 449.

Wielen, R. (1987), in Proceedings of the Tenth Europ.Regional Astron. Meeting of the IAU, Vol. 4, J. Palous (ed.), Publ.Astron.Inst.Czech.Acad.Sci., No. 69, p. 157.

Wielen, R. (1988), in IAU Symposium No. 126, The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies, J.E. Grindlay and A.G.D. Philip (eds.), Kluwer Acad.Publ., Dordrecht, p. 393.

Wielen, R. (1991), in The Formation and Evolution of Star Clusters, K. Janes (ed.), Astron.Soc. of the Pacific, Conference Series, Vol. 13, p. 343.

Wielen, R., Fuchs, B. (1983), in Kinematics, Dynamics and Structure of the Milky Way, W.L.H. Shuter (ed.), D. Reidel Publ.Comp., Dordrecht, p. 81.

Wielen, R., Fuchs, B. (1985), in IAU Symposium No. 106, The Milky Way Galaxy, H. van der Woerden, R.J. Allen and W.B. Burton (eds.), D. Reidel Publ.Comp., Dordrecht, p. 481.

Wielen, R., Fuchs, B. (1988), in The Outer Galaxy, Proceedings of a symposium held in honor of Frank J. Kerr; L. Blitz and F.J. Lockmann (eds.), Lecture Notes in Physics, Vol. 306, Springer-Verlag, Berlin, p. 100.

Wielen, R., Fuchs, B.(1989), in Evolutionary Phenomena in Galaxies, J.E. Beckmann and B.E.J. Pagel (eds.), Cambridge Univ.Press, Cambridge (UK), p. 244.

Wielen, R., Fuchs, B. (1990), in Dynamics and Interactions of Galaxies, R. Wielen (ed.), Springer-Verlag, Berlin, p. 318.

Discussion

FREEMAN: I am curious to understand the difference between your age-velocity dispersion relation and that derived from the recent Stroemgren observations. Your highest velocity dispersion point lies midway between old disk and thick disk values, and your sample of 300 dwarfs might include about 10-15 thick disk stars. Is it possible that age errors from the Ca-emission technique could smooth the Stroemgren form of the σ-τ relation (flat σ-τ for old disk with $\sigma_W \simeq 20\,km/s$ and then $\sigma_W \simeq 40\,km/s$ for the oldest stars) into the form that you show ? How large do you think the Ca-age errors are ?

WIELEN: It is difficult to comment on the AVR based on 'recent Stroemgren observations' as long as neither the AVR nor the basic data and selection procedures have been published in detail or made available to us otherwise. General comments are given in Chapter 3.1 of the present paper. The absolute values of our Ca-ages depend on an assumed star formation rate (e.g. constant in time over 10^{10} years). The relative ages of old K and M dwarfs derived from the CaII emission intensities are probably more accurate than those derived for evolved stars by using isochrones based on stellar-evolution theory. For example, the group of stars with the lowest H and K emission intensities (-2 to -5) represents that 20 % of our sample with the highest ages (between 8 and 10 billion years). The main problem may be to select properly a representative sample of old disk stars.

NEMEC: Isn't the obvious explanation for why your age-velocity dispersion relationship differs from those of Carlberg et al.(1985) and Stroemgren (1987) that the three samples were constructed with different selection effects, causing the mixing proportions of stars from the different stellar populations to be different ?

WIELEN: Maybe. But even then the question remains which sample of stars represents most properly the old disk stars in which we are interested, when discussing diffusion mechanisms, for example.

OSTRIKER: One interesting feature of the massive black hole hypothesis for disc thickening is that it would definitely predict the existence of a thick disc. The break point found in the work I did with Lacey was at about 35 km/s in W.

WIELEN: In this case, the thick disk would not contain only old stars. It should be interesting to calculate the age distribution of stars at various heights z above the galactic plane, predicted from your scenario, and to try to test this prediction by observations.

SPERGEL: Two comments: (1) Numerical simulation done by Bill Bies, a Princeton undergraduate, using Matsuda's hydrocode finds that a triaxial bulge can excite believable spiral structure. (2) Massive black holes would have a dramatic effect on dwarf irregulars. Due to the high dark matter density and small velocity dispersions, MBHs would rapidly heat and disrupt the disks in these systems.

KURUCZ: It is easy to puff up a thin disk. Let there be 10000 globular clusters after the disk is formed. Their orbits carry them through the disk many times before they dissipate. Glancing collisions with disk stars heat the disk. The heating would decrease with radius and would decrease as a function of time as the clusters disintegrate.

WIELEN: This scenario is an interesting proposal. However, I think it meets quantitative difficulties: (a) Even if you put <u>all</u> the mass of the halo into <u>permanent</u> globular clusters of normal mass (say $2 \cdot 10^5$ solar masses each), the heating would be more than 10 times smaller then required by the local diffusion coefficient (derived from the observed AVR). (b) The main source of cluster disruption would be encounters among the globular clusters themselves. If one estimates in this scenario the number of clusters surviving over a Hubble time (by using procedures similar to those applied by Wielen (1985, 1987, 1988, 1991) for calculating the disruption of globular clusters by MBHs), the predicted number of surviving globular clusters is probably higher than we actually observe in our Galaxy.

MATEO: You mentioned that MBHs will destroy globular clusters; yet McClure and van den Bergh pointed out some time ago that the old open clusters are also the ones found furthest from the plane of the Galaxy. Assuming these clusters diffused to their current heights, how can MBHs account for this ?

WIELEN: It is true that massive black holes are also very efficient in destroying older open clusters (e.g. Wielen, 1985). However, distant encounters between MBHs and open clusters can accelerate open clusters (by the total gravitational forces of MBHs) without destroying them (by the tidal forces of MBHs). This would explain old open clusters at high distances z.

CARNEY: Would you expect such a large number of massive black holes to have a disruptive effect on very wide binaries in the disk and in the halo ? By wide, I mean separation of 0.1 pc and up, very loosely bound.

WIELEN: For binaries with separations of about 0.1 pc, the mean disruption time due to massive black holes is roughly of the order of 10^{10} years. Due to the stochastic nature of close encounters between the binaries and MBHs, a significant fraction of such binaries would survive over a much longer time, avoiding by chance close encounters with MBHs. Encounters with giant molecular clouds are probably more dangerous for wide binaries than those with MBHs.

ZINNECKER: Wouldn't it be better to test your predicted colour-height relation for edge-on spirals in the near-infrared (e.g. J-K), where dust extinction is greatly reduced while the sensitivity to metallicity is preserved ?

WIELEN: It is easy for us to use any filter you like. V and B-V, shown in Figs. 4 and 5, have been selected as examples only. We are already making predictions for a large number of colours. The aim is to find an optimum colour in which simultaneously the effect of different ages is maximized and the effect of dust is minimized.