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Stellar kinematics and interstellar turbulence

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Summary. Data assembled from a variety of sources show that the velocity dispersion of young stars and cool interstellar gas increases systematically with the size of the region considered, over a wide range of length scales. This causes an increase of stellar velocity dispersion with age for stars observed near the Sun, since the older stars originate from a larger volume of space. This effect is sufficient to account for the observed age dependence of the velocity dispersion of stars for ages up to about 10^9 yr, implying that secular acceleration is relatively unimportant for the kinematics of the stars. The observed dependence of the gaseous velocity dispersion on region size suggests a turbulent hierarchy of motions in which smaller-scale motions are produced by the turbulent decay of larger-scale ones. Some of the observed large-scale motions, especially those associated with warps of the gas layer, may be driven by gas infall.

1 Introduction

Although it has long been recognized that the velocity dispersion of nearby stars increases systematically with age, the interpretation of this observation in terms of galactic evolution has remained unclear: does it result from a secular decay of turbulent motions in the interstellar medium, or from accelerations acting on stars after they form, as suggested by Spitzer & Schwarzschild (1951, 1953)? Tinsley & Larson (1978) have suggested that the kinematics of stars older than 10^9 yr can be explained by a gradual decay of turbulent motions, as is predicted by plausible collapse models, and have shown that the correlation between velocity dispersion and metallicity predicted by such a model is in agreement with the observations. This effect cannot account directly for the rapid variation of velocity dispersion with age observed even for stars younger than 10^9 yr, but Tinsley & Larson suggested that this could be explained if the velocity dispersion of the youngest stars reflects only the local turbulent motions in the gas, while the velocity dispersion of older stars reflects in addition larger-scale non-circular motions in the galactic gas layer. If the interstellar medium possesses a hierarchy of motions whose velocity dispersion increases with the size of the region considered, older stars which have travelled farther since their formation will sample the gas motions over a larger volume of space, and thus will have a larger velocity dispersion than the younger stars.

That the proposed effect must almost certainly play some role in stellar kinematics is indicated by the properties of some regions of star formation, such as the Orion region. Here stars are forming with a velocity dispersion of only a few km/s (McNamara 1976) from gas that is not in the galactic plane, but is displaced about 120 pc below it. As a result, the Orion stars will later fall through the galactic plane with a systematic velocity of at least ~ 10 km/s, producing a substantially larger velocity dispersion as measured at later times or in larger regions. If disturbances like this on a scale of ~ 1 kpc are superimposed on still larger non-circular motions with scales up to ~ 10 kpc, the stellar velocity dispersion will continue to increase with age up to ages of ~ 10^9 yr, which is the time required for stars with a random velocity of ~ 10 km/s to disperse over 10 kpc.

The relation between gaseous velocity dispersion and region size that is required if such interstellar motions are to explain the dependence of the stellar velocity disperion σ on age τ can be estimated from the approximate empirical relation $\sigma \propto \tau^{1/2}$ found by Wielen (1977). If σ is equal to the velocity dispersion of the gas in a region of size L in which the stars of age τ have originated, then since $L \sim \sigma\tau$, we obtain $\sigma \propto L^{1/3}$. The agreement between this and the Kolmogoroff spectrum for incompressible turbulence is suggestive, if perhaps only accidental. The Kolmogoroff law depends on the assumption that energy is successively transferred into motions on smaller and smaller scales until it is dissipated by viscosity. This may not be a good assumption if the motions are supersonic, as in the interstellar medium, since energy can then be directly dissipated on large scales by shock fronts; this leaves less energy for small-scale motions, and produces a steeper dependence of σ on L. For example, if all of the dissipation occurs in a random assembly of shock fronts, then $\sigma \propto L^{1/2}$ (Kraichnan 1974). It is, of course, possible that interstellar motions on different scales have entirely different origins (e.g. supernovae, density wave effects, etc.), in which case it would be coincidental if there were any simple relation between σ and L. In Section 2 we consider some of the relevant observational evidence concerning the relation between σ and L; possible implications of these data for the origins of the interstellar motions will be considered further in Section 4.

The conventional explanation for the increase of stellar velocity dispersion with age, suggested by Spitzer & Schwarzschild (1951, 1953) and supported by Wielen (1977), is that stars are randomly accelerated by encounters with massive gas clouds or complexes. As noted by Wielen, the identification of suitable mass concentrations is a 'delicate problem'; although large gas complexes do exist and should presumably produce some effect, it is not clear whether this effect is sufficient. A constraint on the proposed random accelerations is set by the existence of fairly old moving groups of stars which are spatially dispersed but have small velocity dispersions. This is evident in fig. 1 of Eggen (1969), which shows that the distribution in velocity space of F stars younger than NGC 752 (age 1.7×10^9 yr, from McClure & Twarog 1977) is not random but is strongly clumped. (The same effect is seen in an independent sample of F stars from M. Mayor (B. M. Tinsley, private communication).) The most prominent clump in the velocity diagram is the Hyades moving group, whose reality is supported by the photometry of Boyle & McClure (1975). From Eggen's diagram, the U and V velocity dispersions for the Hyades group are approximately $\sigma_U \lesssim 6$ km/s and $\sigma_V \lesssim 3$ km/s, yielding a total 3-dimensional dispersion of $\sigma \lesssim 7$ km/s. The age of the Hyades group is 7×10^8 yr (McClure & Twarog 1977), and after this time the random accelerations postulated by Wielen (1977) would have produced a total velocity dispersion of $\sigma \sim 20$ km/s, much larger than the observed velocity dispersion of the Hyades group. Thus either the amount of random acceleration is too small to explain the age dependence of the stellar velocity dispersion, or the accelerating forces must be coherent over sufficiently large distances that they act equally on all the Hyades group stars. In any case it seems worthwhile to examine the simpler possibility that the motions of old stars and groups of stars are due to the motions of the gas from which they were formed.

2 Observed velocity dispersion of stars and gas

Data on the velocity dispersions of young stars and interstellar gas in regions of different size have been collected in order to determine whether the velocity dispersion σ shows any systematic dependence on region size L. The length scales which are most relevant for understanding the age dependence of the stellar velocity dispersion are those between about 200 pc and 20 kpc; velocity dispersions on scales smaller than ~ 200 pc are not directly relevant, since they are already included in the usually quoted stellar velocity dispersions. Nevertheless, in the hope of contributing to a better understanding of interstellar gas dynamics on all scales, we have included some data on velocity dispersions in regions as small as ~ 1 pc.

2.1 VELOCITY DISPERSIONS OF YOUNG STARS

Relevant data on the motions of young stars in regions of different size include the velocity disperions of young open clusters, associations and subassociations of various sizes, and OB stars within various distances of the Sun.

The smallest region for which a velocity disperion can (in principle) be determined is a single young cluster, having a typical diameter of perhaps 4 kpc and a mass of order $10^3 M_\odot$ (Burki 1978). In the absence of sufficiently accurate direct measurements for any such clusters, we adopt a virial theorem estimate of $\sigma = 1.5$, where σ hereinafter denotes the 3-dimensional rms random velocity in km/s, calculated assuming an isotropic velocity distribution. For T associations, which have typical diameters of ~ 20 pc, Herbig (1962, 1977) has estimated a one-dimensional velocity dispersion of ~ 2 km/s, which gives $\sigma \sim 3.4$. Similar results are found for the subregions of O associations (Blaauw 1964), which have typical diameters of ~ 40 pc and velocity dispersions of the order of $\sigma \sim 4$ (Blaauw 1964; McNamara 1976). For a whole O association containing several subgroups, a typical diameter is ~ 120 pc and a typical velocity dispersion, including the relative motions of the subgroups, is ~ 7 km/s (Blaauw 1964; Lesh 1972). Data on the velocities of all the OB stars near the Sun have been compiled by Frogel & Stothers (1977); for B0–B2 stars within 200 pc of the Sun they find $\sigma = 12$, while for stars with distances between 200 and 400 pc the result (after correction for formal errors) is $\sigma = 18$. Part of the increase of σ with distance may be due to increased errors, but Frogel & Stothers note that part of it may also be a real effect due to large-scale relative motions between O associations.

The data thus show a clear trend of increasing velocity dispersion with increasing region size. It is especially significant for the present purposes that Frogel & Stothers find an increase with distance out to at least 400 pc, because when stars originating at such distances pass near the Sun after ~ 4×10^7 yr, they will have a larger velocity dispersion than local newly formed stars; thus there will be an apparent increase of velocity dispersion with age. The data given above for the velocity dispersion of stars as a function of region size are summarized in Table 1, and plotted in Fig. 1 (crosses). We note that the dependence of σ (km/s) on region size L (pc) as indicated by these data can be represented approximately by $\sigma = 0.9 L^{0.43}$ for $4 \leqslant L \leqslant 800$ pc.

Table 1. Velocity dispersions of young stars and gas in regions of various sizes.

Region or type of observation	Diameter L (pc)	σ (km/s)*
Young stars:		
Young open cluster	4	1.5
T association	20	3.4
O association subgroup	40	4
O association	120	7
B0–2 stars within 200 pc	400	12
B0–2 stars between 200 and 400 pc	800	$\leqslant 18$
Interstellar gas:		
Dark cloud	1.4	1.1
H I or CO cloud	10	3
H I or CO complex	100	5
H I clouds within ~ 300 pc	600	11
Local (Gould belt) gas flows	1000	13
Irregularities in rotation curve	2000	15
Warps in gas layer, $R \sim 10$ kpc	5000	17
Asymmetry of rotation curve	10 000	19
Warps in gas layer, $R \sim 15$ kpc	30 000	~40
Other galaxies:		
M31 21-cm profile dispersions	2000	20
M31 H II region rotation curve	5000	21
M31 minor axis motions	30 000	32
M31 outer warp	60 000	~60
M81 minor axis motions	20 000	20
M81 outer distortions	30 000	~30

* σ is the 3-dimensional RMS random velocity.

2.2 VELOCITY DISPERSIONS OF GAS MOTIONS

We are interested here only in the motions of the relatively cool gas or gas clouds from which stars might form. Relevant data include the internal velocity dispersions of clouds and cloud complexes of various sizes, the velocity dispersion of cloud motions, and large-scale deviations from circular and coplanar motion of the galactic gas layer, including those associated with irregularities in the galactic rotation curve and warps in the gas layer. Weaver (1970) has previously noted that interstellar motions on different scales seem to have a hierarchical character, the small-scale motions appearing as disturbances superimposed on larger-scale motions with larger velocities.

We mention first the dark clouds described by Heiles (1971), which have a typical diameter of 1.4 pc and a typical velocity dispersion σ of about 1.1 km/s. For the 'standard' H I clouds, the 21-cm data compiled by van Woerden (1967) yield a typical diameter of $L \sim 10$ pc and an internal velocity dispersion of $\sigma \sim 3$. For CO clouds, Zuckerman & Palmer (1974) quote $L \sim 10$ pc and $\sigma \sim 3$, i.e. the same values as for the H I clouds, despite the much higher densities and masses of the CO clouds. For larger complexes or 'sheets' of H I, the observations reviewed by Heiles (1974) suggest typical dimensions of $L \sim 100$ pc and velocity dispersions of $\sigma \sim 5$. Again, similar results are found for CO complexes: for example, Kutner *et al.* (1977) find that the molecular gas associated with the dark cloud

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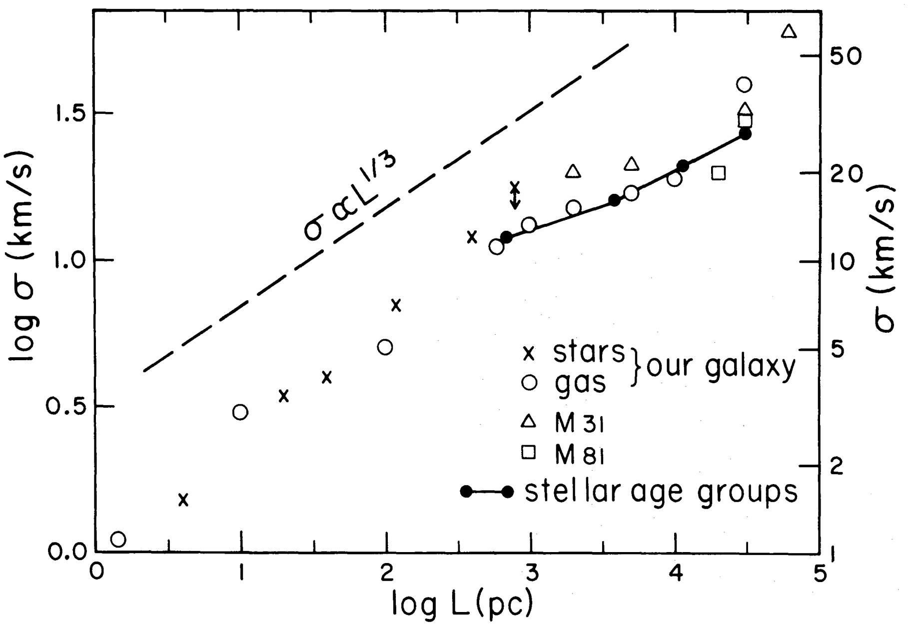

Figure 1. The three-dimensional velocity dispersion σ versus region diameter L from Table 1 for young stars (crosses) and interstellar gas (open circles) in our Galaxy. Also shown are data for the velocity dispersion of the gas in M31 (triangles) and M81 (squares). The dots and solid line give the relation between velocity dispersion and diameter of the region of origin for stars in different age groups from Table 2.

L1641 in Orion extends over $L \sim 70$ pc and has a velocity dispersion $\sigma \sim 6$, while Elmegreen & Lada (1976) find $L \sim 85$ pc and $\sigma \sim 4$ for a CO complex associated with M17.

The velocity dispersion of H I cloud motions has been determined by Falgarone & Lequeux (1973) from both 21-cm and optical absorption lines, and they obtain $\sigma = 11$ for clouds within about 300 pc of the Sun. Extensive 21-cm surveys (e.g. Weaver 1974) show, in addition to the random cloud motions, larger-scale systematic gas flows apparently associated with the Gould belt: gas is observed to be flowing into the galactic plane from both sides with a mean velocity of at least 10 km/s, and it then spreads out into the Gould belt with a velocity of several km/s. As a conservative estimate of the total velocity dispersion of all of the gas motions, both random and systematic, in the region of the Gould belt, which has a total extent of $L \sim 1$ kpc, we adopt $\sigma \sim 13$.

Information about non-circular gas motions on larger scales can be obtained, albeit less directly, from irregularities in the galactic rotation curve and from the warps in the galactic gas layer (of which the Gould belt may be a local example). A recent study of galactic rotation by Burton & Gordon (1978), based on both H I and CO data, allows the velocity dispersion of non-circular motions to be estimated from the rms deviation of the observed maximum rotational velocities from a smooth rotation curve. For H I we obtain, assuming an isotropic velocity distribution, a 3-dimensional rms non-circular velocity of ~12 km/s; to this must be added the small-scale velocity dispersion of gas in the telescope beam, which is typically 9 km/s, to yield a total velocity dispersion of $\sigma \sim 15$. For CO the determination is simpler since the beam velocity dispersion is unimportant, and the scatter of the points about a smooth rotation curve yields directly $\sigma \sim 15$, in agreement with the 21-cm result (and with Burton & Gordon's conclusion that CO and H I have the same kinematics). A characteristic scale length for these fluctuations is estimated to be $L \sim 2$ kpc.

The galactic gas layer deviates from a plane by up to ~50 pc in the inner part of the Galaxy (Lockman 1977), and the deviations increase rapidly outside the solar distance from the Galactic Centre (Kerr 1969), being about ±100 pc at $R = 10$ kpc and ±200 pc at $R = 12$ kpc. The velocities of the vertical motions associated with these warps can be calculated from a standard galactic mass model (e.g. Schmidt 1965) and they correspond to a 3-dimensional velocity dispersion of ~11 km/s at $R = 10$ kpc, if an isotropic velocity distribution is assumed. Superimposed on these large-scale effects are the motions on scales smaller than ~1 kpc for which a velocity dispersion of ~13 km/s was estimated above; this gives a total dispersion of $\sigma \sim 17$ on a length scale of $L \sim 5$ kpc, which is the distance over which vertical deviations of ±100 pc occur, as estimated from Kerr's fig. 6. An independent estimate of the RMS non-circular velocity on a scale of ~10 kpc can be made from the asymmetry between the rotation curves on the northern and southern sides of the Galaxy, which differ by up to ~10 km/s (Kerr 1969); converting this to a 3-dimensional rms velocity and adding the dispersion of ~15 km/s estimated above for small-scale irregularities in the rotation curve, we obtain a total dispersion of $\sigma \sim 19$ on a scale $L \sim 10$ kpc. Finally, an estimate based on the amplitude of the outer warp at $R \sim 15$ kpc yields $\sigma \sim 40$ for $L \sim 30$ kpc; this is approximately consistent with other indications of the amount of non-circular motion in the outer part of our galaxy (Burton 1974; Verschuur 1975).

These estimates of the velocity dispersion of the gas are summarized in Table 1 and plotted in Fig. 1 (circles). As with the stellar data, a monotonic increase of velocity dispersion with region size is seen, and the data for young stars and gas agree well where they overlap. Thus the assumption that the stars form with the same velocity dispersion as the gas seems well justified. We also note that the estimates based on irregularities in the rotation curve and those based on warps in the gas layer are quite consistent with each other; this suggests that the horizontal and vertical gas motions are part of the same general phenomenon, and supports our assumption of an isotropic velocity distribution.

2.3 NON-CIRCULAR MOTIONS IN OTHER GALAXIES

Because the above estimates of the velocity dispersion of large-scale gas motions are somewhat indirect, and because it is important to obtain accurate values, we have attempted to supplement these results with data on non-circular motions in two similar nearby spiral galaxies, M31 and M81. Non-circular motions of at least 10 km/s are universally observed in spiral galaxies, and an extensive discussion of non-circular motions in galaxies has been given by Bosma (1978).

In an extensive 21-cm study of M31, Emerson (1976) finds a velocity dispersion equivalent to $\sigma \sim 20$ for the gas in the telescope beam, which covers a region of maximum extent $L = 2$ kpc in the plane of the Galaxy. A velocity dispersion can also be estimated from the measurements of Rubin & Ford (1970) of the radial velocities of H II regions; the scatter of these velocities about a smooth rotation curve yields, correcting for measurement errors, $\sigma \sim 21$ in a region of size $L \sim 5$ kpc. From Emerson's data for the radial velocities on the minor axis of M31, the rms non-circular velocity in three dimensions is calculated to be 26 km/s; adding a velocity dispersion of 20 km/s for gas in the telescope beam, we obtain a total dispersion of $\sigma \sim 32$ in a region of diameter $L = 30$ kpc. On a still larger scale, from the amplitude of the warp in the outermost part of M31 (Roberts & Whitehurst 1975; Newton & Emerson 1977), we obtain a rough estimate of $\sigma \sim 60$ on a scale $L \sim 60$ kpc.

For M81, an estimate of the amount of non-circular motion can be made from the 21-cm measures of Rots (1975) of the radial velocities along the minor axis. The rms fluctuation of these velocities yields a 3-dimensional velocity dispersion of 15 km/s; adding an assumed dispersion of 13 km/s (see above) for motions on scales smaller than the telescope beam of ~1 kpc, we obtain $\sigma \sim 20$ on a scale $L = 20$ kpc. Outside 10 kpc from the centre of M81, the velocity field is strongly distorted from circular coplanar motion (apparently partly by interaction with a small companion), and a crude estimate of the magnitude of this effect yields $\sigma \sim 30$ for $L = 30$ kpc.

The data for M31 and M81 are included in Table 1 and Fig. 1 for comparison with the results for our own Galaxy. It appears that M31 has more non-circular motion on most scales than our Galaxy, while M81 may have slightly less. More significant, however, is the fact that all three galaxies have random or non-circular velocities that are of the same order and increase in a similar way with length scale. These results support the estimated velocity dispersions previously derived for our Galaxy, and suggest that our Galaxy is fairly typical in this respect.

3 Implications for stellar kinematics

The data discussed above strongly suggest that the interstellar gas and young stars in our Galaxy possess a hierarchy of motions whose velocity dispersions increase systematically with increasing length scale. Moreover, different measures of the amount of random motion, whether for H I clouds, CO clouds or young stars, all yield consistent values for the velocity dispersion as a function of length scale. These results imply, whatever the origin of the observed motions, that the velocity dispersion of stars near the Sun must increase systematically with age, since the older stars have moved farther since their formation and thus sample the gas motions over a larger volume of space.

The age dependence of the stellar velocity dispersion found for Wielen's (1977) stellar age groups can be compared with that predicted from the above data by plotting the stellar velocity dispersion σ versus the diameter L of the region of origin for the stars in each age group, and comparing with the data in Fig. 1. The ages, velocity dispersions and initial region sizes L for the groups with ages up to 10^9 yr are given in Table 2. In calculating the region size L, it is necessary to take into account that the stars perform epicyclic oscillations about a guiding centre, so that after one-quarter of an epicyclic period or about 5×10^7 yr their spatial dispersion occurs mainly in the azimuthal coordinate and is due to the different orbital periods of their guiding centres. Most of the stars in Wielen's age groups have ages greater than one-quarter of an epicyclic period, and therefore only the one-dimensional velocity dispersion $\sigma/\sqrt{3}$ has been used in calculating the diameter L of their region of origin; for stars of age τ, we then have approximately $L = 2\sigma\tau/\sqrt{3}$. A more rigorous calculation taking into account the exact epicyclic orbits and the anisotropy of the velocity distribution yields almost exactly the same result for L.

The values of σ and L for the stellar age groups of Table 2 are plotted in Fig. 1 (dots joined by straight lines) for comparison with the observed non-circular gas motions (circles). The agreement is seen to be quite close for length scales up to at least $L = 10$ kpc,

Table 2. Velocity dispersion and size of region of origin for the stellar age groups of Wielen (1977).

Age (Myr)	σ (km/s)	L (pc)
50	12	690
210	16	3 900
470	21	11 000
1000	27*	31 000

* Interpolated from smooth curve.

corresponding to ages up to at least 5×10^8 yr. The largest length scale relevant for the present purposes is $L \sim 20$ kpc, since a star in a nearly circular orbit can get no farther than this from its point of origin; the corresponding age is nearly 10^9 yr. Although the data in Fig. 1 become more scattered on the largest scales, the agreement remains good, and the observations do not clearly contradict the hypothesis that the age dependence of the velocity dispersion for stars younger than $\sim 10^9$ yr is due to the increase of the gaseous velocity dispersion with region size. Of course, this effect cannot account for the continuing increase of velocity dispersion with age for stars older than 10^9 yr, but the older stars may be affected by a long-term gradual decay of turbulent motions on all scales, and this could account for most or all of the age dependence of the velocity dispersion for older stars (Tinsley & Larson 1978).

The agreement between the predicted and observed stellar velocity dispersions shown by Fig. 1 sets an upper limit on the amount of random acceleration that can have been experienced by stars during the past 10^9 yr. If, for example, we take the point farthest below the solid line in Fig. 1 (i.e. $\sigma = 20$ at $L = 20$ kpc for M81) and assume that it applies also to our Galaxy, the difference between this and the value $\sigma = 24$ interpolated from the solid line at $L = 20$ kpc leaves a maximum dispersion of ~ 14 km/s to be accounted for by accelerations. If a maximum dispersion of, say, 15 km/s can be produced by random accelerations in 10^9 yr, the diffusion coefficient C_v must be at most 1/3 as large as found by Wielen (1977). The Hyades moving group, as discussed in Section 1, sets an even stronger limit on random acceleration during the past 7×10^8 yr, implying a diffusion coefficient less than one-tenth of Wielen's value. We conclude that random accelerations are probably relatively unimportant, and that most of the observed velocity dispersion of stars results from the initial motions of the gas from which they formed.

4 Possible implications for interstellar gas dynamics

From Fig. 1, it is clear that any adequate understanding of the irregular or 'turbulent' motions in the interstellar medium must account for the systematic increase of their characteristic velocities with increasing length scale. Evidently, no mechanism (e.g. supernovae) which produces motions with only a single length scale or characteristic velocity can by itself explain the full spectrum of interstellar motions. A broad spectrum of motions could, however, be produced in a turbulent flow in which large-scale motions decay as a result of various instabilities into motions on smaller and smaller scales, which thus derive their energy from the large-scale motions. The application of turbulence theory, including the Kolmogoroff law, to interstellar motions was earlier proposed by von Weizsäcker (1949). In Fig. 1 the dashed line shows the slope of the Kolmogoroff spectrum for incompressible turbulence, $\sigma \propto L^{1/3}$, and it can be seen that the observed relation between σ and L shows at least a superficial resemblance to this law over a wide range of scales.

Supersonic flows in the interstellar medium may be at least as subject as incompressible flows to instabilities tending to degrade large-scale motions into smaller-scale ones. This is suggested, for example, by Woodward's (1976, 1978) detailed calculations of the interaction of an interstellar cloud with a shock front in an intercloud medium; both Kelvin–Helmolz and Rayleigh–Taylor instabilities occur and distort the cloud into a very irregular ragged shape, eventually shredding it into pieces which may then break up into still smaller pieces. In this way a significant fraction of the kinetic energy of large-scale motions might be transferred into smaller-scale motions.

If the mean free path for such turbulent motions is approximately equal to their length scale L, the rate of dissipation of energy per unit mass for motions on scale L is $\sim \sigma^3/L$; thus if σ^3/L is observed to increase with L, it is at least energetically feasible for the smaller-scale motions to derive their energy from the dissipation of larger-scale ones.

For scales smaller than 1 kpc, Fig. 1 suggests that the increase of σ with L is in fact slightly steeper than $L^{1/3}$; within the uncertainties, the data for $L \lesssim 1$ kpc can be represented by $\sigma \simeq 1.1\,L^{0.37}$. This is intermediate between the Kolmogoroff law and the relation $\sigma \propto L^{1/2}$ appropriate for a system of random shock fronts. Thus it seems at least energetically possible for the interstellar motions on scales smaller than 1 kpc to derive their energy from larger-scale motions by some sort of turbulent cascade process. This could have important implications for those small-scale motions that form molecular clouds and thus lead to star formation; the star formation rate might depend on the velocities of such small-scale motions, and so might be controlled ultimately by larger-scale motions, if the turbulent cascade concept is applicable. There is, in fact, evidence that large-scale disturbances in galaxies produce enhanced rates of star formation (Larson & Tinsley 1978). In any case, as an alternative to the conventional explanations of the small-scale motions as resulting from supernova explosions, etc., it seems worthwhile to keep in mind the possibility of their origin from the decay of large-scale motions.

For length scales between about 1 and 20 kpc, Fig. 1 indicates that σ increases more slowly with L than $L^{1/3}$; in this range of length scales the interstellar velocity dispersion in our Galaxy is given approximately by $\sigma \simeq 4.4\,L^{0.16}$. Since this is the range of length scales in which the dynamics is dominated by galactic rotation and the motions of interest are merely perturbations on circular orbits, it is not surprising that a different relation between σ and L should hold than for smaller scales. In this situation there is not enough energy in the large-scale non-circular motions to power the smaller-scale motions directly by a turbulent cascade process, so additional mechanisms are necessary to explain the motions on scales near $L \sim 1$ kpc. Relatively conventional possibilities include density waves, gravitational instabilities of the galactic gas layer and (conceivably) bursts of star formation and supernova production. However, a shortcoming of these mechanisms is that they offer no ready explanation for the tilt of the Gould belt, or for the other observed vertical displacements or warps of the galactic gas layer on scales of a few kpc. Possible explanations of such small-scale warps include (1) differential precession effects acting in a system with a large-scale initial warp to produce small-scale corrugations, and (2) disturbances produced by gas streams flowing in from outside the galactic plane, as suggested by Weaver (1974) to explain the Gould belt.

If the warps in question involve only the gas layer and not the total mass of the galactic disk, the rate of precession of gas rings at different radii can be calculated from a standard galactic mass model (Schmidt 1965). It is found that, almost independently of radius, the time required for a gas layer with a large-scale warp to develop corrugations of wavelength L is approximately $\Delta t(\mathrm{yr}) \sim 4 \times 10^{11}/L(\mathrm{pc})$. For example, the time required to develop corrugations of wavelength 2 kpc is about 2×10^8 yr. (Similar time-scales are obtained if the total mass of the galactic disk participates in the warps (Hunter & Toomre 1969).) If there is little dissipation of the vertical motions during this time, the amplitude and velocity of the vertical oscillations of the gas layer will not decrease much while their wavelength decreases from (say) 20 to 2 kpc. In fact, the turbulent dissipation time-scale L/σ is about 10^9 yr for $L = 20$ kpc, and remains longer than the differential precession time for all wavelengths greater than $L \sim 2.5$ kpc, for which both times are about 1.6×10^8 yr. Thus, if short-wavelength disturbances are generated from larger-scale ones by differential precession effects, the variation of characteristic velocity σ with length scale L will be relatively slow for scales between about 2 and 20 kpc, and more rapid for scales smaller than 1 kpc where dissipation becomes important; this prediction is in qualitative agreement with the observations (Fig. 1).

The second possible explanation of the small-scale vertical displacements and warps of the galactic gas layer, namely inflow of gas streams from outside the galactic plane, is attractive in that similar phenomena occurring on larger scales may also account for the large-scale warps of the galactic gas layer (Larson 1976; Saar & Einasto 1977). Evidence that gas inflows influence the dynamics of local interstellar matter is provided by the observations reviewed by Weaver (1974) showing that the nearby low-velocity gas above and below the galactic plane is flowing toward the plane at about 10 km/s. An inflow is also observed in the intermediate-velocity gas at high galactic latitudes, as studied by Wesselius & Fejes (1973). Here, a large concentration of negative-velocity gas is found to coincide with a hole in the low-velocity gas, indicating that part of the low-velocity gas above the galactic plane has been strongly accelerated toward the plane; according to Wesselius & Fejes, the most likely cause is an infalling gas complex or stream.

Another example of a concentration of negative-velocity gas that coincides with a hole in the low-velocity gas has been noted in the galactic anticentre direction by Burton & Moore (1978); again, a possible explanation is that the low-velocity gas has been disturbed by a stream of infalling gas. The possibility that streams of gas are presently falling into the galactic disk from outside is further suggested by the fact that many of the high-velocity clouds discussed by Davies (1972, 1974), Verschuur (1975) and Hulsbosch (1975) appear to occur in bands which can be interpreted as infalling streams (Larson, in preparation).

5 Conclusions

From the data compiled in Section 2 and shown in Fig. 1, it appears that galaxies similar to our own possess turbulent or non-circular gas motions whose velocity dispersion increases systematically with increasing length scale. Different galaxies probably possess different amounts of non-circular motion; M31 seems to have larger non-circular motions than our Galaxy or M81. The increase in gaseous velocity dispersion with increasing region size leads to an increase of the stellar velocity dispersion with age, because the older stars have travelled farther since their formation and thus sample the gas motions over a larger volume of space. The agreement between the gaseous and stellar velocity dispersions illustrated in Fig. 1 shows that the observed gas motions are sufficient to account for the increase of the stellar velocity dispersion with age for ages up to $\sim 10^9$ yr; consequently, random accelerations of stars must play a relatively unimportant role in stellar kinematics. This conclusion is consistent with the existence of the Hyades moving group, which has been relatively little dispersed in velocity during the past 7×10^8 yr.

The increase in gaseous velocity dispersion with length scale also has implications for the origins of the observed random or non-circular motions in galaxies. If different mechanisms produce the motions on different scales (e.g. supernovae, density wave effects, etc.), those which act on larger scales must also generate larger velocities, as required by the observations. An alternative possibility that seems more economical of hypotheses is that a turbulent hierarchy of motions is present in which large-scale motions decay into smaller-scale ones as a result of various instabilities; a driving mechanism is then required only for the largest-scale motions, and the smaller-scale ones are powered by a turbulent cascade process. The observations are consistent with this possibility for scales smaller than ~ 1 kpc; on larger scales, differential precession effects may help to generate small-scale motions from large-scale ones. The ultimate source of the non-circular motions in the Galaxy seems most likely to be some form of external perturbing influence, such as the accretion of gas, perhaps in streams, by the Galaxy (Larson 1972; Saar & Einasto 1977).

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