STELLAR KINEMATICS AND INTERSTELLAR TURBULENCE

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1. INTRODUCTION

It is well known that the velocity dispersion of nearby stars increases systematically with age, and this fact is conventionally explained by postulating that stars are randomly accelerated by encounters with massive gas clouds (Spitzer & Schwarzschild 1951, 1953; Wielen 1977). However, a strong constraint on the possible role of random accelerations is provided by the apparent existence of fairly old moving groups of stars (Eggen 1969, Boyle & McClure 1975). An alternative explanation (Tinsley & Larson 1978) is that the age dependence of the velocity dispersion of stars older than 10^9yr is produced by a gradual decay with time of interstellar turbulent motions, as predicted by plausible collapse models. This effect cannot account directly for the variation of velocity dispersion with age observed for stars younger than 10^9yr, but Tinsley & Larson suggested that this could be explained if the velocity dispersion of the youngest stars reflects only the local turbulent motions of 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 traveled 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.

Here we summarize some data on the velocity dispersions of interstellar gas and young stars which show that the increase of velocity dispersion with region size is, in fact, sufficient to account for the age dependence of the stellar velocity dispersion for ages up to $\sim 10^9$yr. Further details and references are given by Larson (1978).

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 233–237.

https://doi.org/10.1017/S0074180900014534 Published online by Cambridge University Press

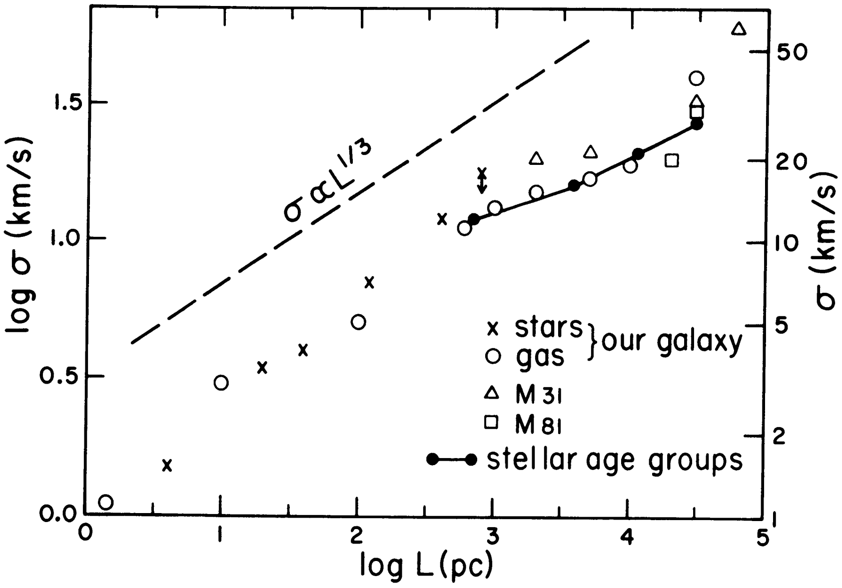

Figure 1. The 3-dimensional velocity dispersion σ versus the diameter of the region in which σ is measured.

2. VELOCITY DISPERSIONS OF STARS AND GAS

Data have been collected from a variety of sources for the velocity dispersions of young stars and gas in our galaxy and in M31 and M81, as measured in different ways and in regions of different size. The observations used are listed below; given in parentheses for each case are the values of (σ, L), where σ is the estimated 3-dimensional RMS random velocity (km/s) and L is the diameter (pc) of the region in which σ is measured. The resulting dependence of σ on L is plotted in Figure 1.

Data on the velocity dispersions of young stars in regions of different size include the following: the velocity dispersion of a typical young open cluster (1.5, 4); the velocity dispersion of a typical T association (3.4, 20); a typical subgroup of an O association (4, 40); a whole O association (7, 120); OB stars within 200 pc of the sun (12, 400); and OB stars with distances between 200 and 400 pc ($\lesssim$ 18, 800). These data are plotted as crosses in Fig. 1, and a regular increase of σ with L is evident.

Data for cool interstellar gas or gas clouds include: the internal velocity dispersion of a typical dark cloud (1.1, 1.4); a typical HI or CO cloud (3, 10); a typical HI or CO cloud complex (5, 100); and the velocity dispersion of HI clouds within ∿ 300 pc of the sun (11, 600). For larger length scales, velocity dispersions can be estimated from observations of non-circular gas motions, if isotropic motions are assumed and if the velocity dispersions of the smaller-scale motions

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that are not included are added in. Such observations include: local gas flows associated with the Gould belt (13, 1000); irregularities in the galactic rotation curve (15, 2000); vertical motions associated with warps or corrugations of the galactic gas layer (17, 5000); the large-scale asymmetry of the rotation curve (19, 10000); and non-circular motions and warps in the outermost part of the galaxy (∿40, 30000). These data are plotted as circles in Fig. 1.

Data for non-circular motions in other galaxies include: the small-scale velocity dispersion of HI in M31 (20, 2000); the velocity dispersion of HII regions in M31 (21, 5000); non-circular motions on the minor axis of M31 (32, 30000); motions associated with the outer warp of M31 (∿60, 60000); minor axis motions in M81 (20, 20000); and non-circular motions in the outer part of M81 (∿30, 30000). These data are shown as triangles and squares in Fig. 1. Note that, while M31 seems to show somewhat larger non-circular motions than our galaxy or M81, all three galaxies show non-circular velocities of comparable magnitude which increase in a similar systematic way with increasing length scale. Also, the results for young stars and gas agree well where they overlap, supporting the assumption that the stars form with the same velocity dispersion as the gas.

3. IMPLICATIONS FOR STELLAR AND GAS DYNAMICS

The observed (σ, L) relation for the interstellar motions shown in Fig. 1 can be compared with that required to explain the age dependence of the stellar velocity dispersion by plotting the velocity dispersions of Wielen's (1977) stellar age groups versus the diameter of the region of origin for the stars in each group. Assuming that these stars disperse principally in the azimuthal direction, since their ages are mostly greater than one-quarter of an epicyclic period, the diameter L of the region of origin for stars of age τ and velocity dispersion σ is $L \sim 2\sigma\tau/\sqrt{3}$. The resulting ($\sigma$, L) relation for the groups with ages up to 10^9yr is indicated by the dots joined by solid lines in Fig. 1.

It is seen that the agreement between the velocity dispersions of gas and stars as a function of effective region size is quite close for region sizes up to at least 10 kpc, corresponding to ages up to 5×10^8yr, and remains good for scales up to 20 kpc, or ages of nearly 10^9yr. This agreement means that most of the age dependence of the stellar velocity dispersion is due to the increase of σ with L for interstellar motions, and it sets an upper limit on the possible importance of random accelerations; in terms of Wielen's diffusion coefficient, a value at most 1/3 as large as that derived by Wielen is allowed by these data. This is consistent with the existence of the Hyades moving group, which suggests a diffusion coefficient not more than 1/10 of Wielen's value (Larson 1978).

The (σ, L) relation shown in Fig. 1 also has implications for the origin and dynamics of the observed gas motions. Clearly no single mechanism, e.g. supernova explosions, that produces motions with only a limited range of velocities or length scales can account for 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 through various instabilities into smaller-scale motions, which thus derive their energy from the larger-scale motions. The dashed line in Fig. 1 shows the slope of the Kolmogoroff spectrum $\sigma \propto L^{1/3}$ for incompressible turbulence, and the observations bear at least a superficial resemblance to this relation. Thus it is at least energetically feasible for the smaller-scale interstellar motions to derive part of their energy from larger-scale motions via a turbulent cascade process.

The short time ($<10^9$yr) required for the decay of non-circular motions implies a continuing energy input for at least the largest-scale motions. The existence of the Gould belt and other vertical displacements of the galactic gas layer suggests that mechanisms internal to the galactic disk are not entirely adequate, and that external perturbations act on the galactic gas layer. An attractive possibility for explaining some of the observed random or non-circular motions of the gas layer is infall of gas from outside the galactic disk (Larson 1972, Saar & Einasto 1977).

4. CONCLUSIONS

The observed non-circular interstellar motions are sufficient to explain the age dependence of the stellar velocity dispersion for ages up to $\sim 10^9$yr; thus it appears possible to understand the kinematics of stars in terms of the initial turbulent motions of the gas, without invoking random accelerations. It is therefore important for both stellar dynamics and interstellar gas dynamics to understand the origin of the observed gas motions on various scales. Interactions with material outside the galactic plane may play a role in producing some of these motions.

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DISCUSSION

de Vaucouleurs: I am curious to find out what would be the slope of your σ_v,L diagram if you reinterpreted it as a density, L diagram using the virial theorem.

Larson: If you adopt the relation $\sigma \propto L^{1/3}$, which is roughly satisfied empirically, and associate a density ρ with each L and σ via the virial theorem, you obtain $\rho \propto L^{4/3}$. This gives the density which regions of different size would have to have in order to be gravitationally bound. Some representative densities predicted this way are $n \sim 10^4$ cm^{-3} for L = 1 pc, $n \sim 10^3$ cm^{-3} for L = 10 pc, $n \sim 2$ cm^{-3} for L = 1 kpc, and $n \sim 0.1$ cm^{-3} for L = 10 kpc. I leave it to the reader to decide whether the rough coincidences between these numbers and the observed densities of interstellar structures or regions of different sizes are meaningful.

Innanen: The existence of a third "quasi" integral of motion demands a strongly anisotropic velocity distribution function. Consequently its operation will assure the persistence of the anisotropy and no "collisional accelerating " mechanism is therefore required.

Larson: Actually I assumed isotropic velocity dispersions throughout, but this makes no significant difference to the conclusions. You are right that an anisotropic velocity distribution would be preserved by the third integral if random accelerations are not important, and therefore the anisotropy might also be a result of initial gas motions. If the gas motions are maintained by a balance between an energy input and turbulent dissipation, the observed anisotropy might reflect the fact that the oscillation period of vertical motions is shorter than the epicyclic period, perhaps resulting in a faster dissipation of vertical gas motions and a smaller velocity dispersion in the vertical direction than parallel to the galactic plane.

Wielen: (1) Typical disk stars have a total velocity dispersion of about 60 km s^{-1}. Do you suggest that this was the typical non-circular velocity of the gas during the past history of the galactic disk? (2) What are the typical time scale (age) and the typical length scale over which a sufficient mixture has occurred among the younger disk stars in order to show the large-scale velocity dispersion according to your theory?

Larson: (1) Yes, I suggest that this was the velocity dispersion of the gas motions at the time when the "typical" disk stars in the solar neighborhood formed, perhaps some 5×10^9 years ago. (2) It takes $\sim 10^9$ years for stars to disperse completely around an annulus of radius 10 kpc, so only stars older than this can be considered to be "completely mixed". If the velocity dispersion of the gas increases monotonically with length scale, it is necessary to integrate the characteristics of younger stars over a complete annulus of radius 10 kpc in order to compare their properties with older stars and study the long-term effects of galactic evolution.

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