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THE MILKY WAY LOCAL DYNAMICS

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Abstract. The dynamics of our own Galaxy (the Milky Way) in the solar neighbourhood is analyzed. It is emphasized that in the framework of the classical approach, which involves the steady state and axial symmetry, the main research directions are the determination of the dynamical constants and the explanation of the local kinematics. In spite of this it seems that the classical approach is not sufficient to explain the entire variety of the observed phenomena. Some of them (vertex deviation, velocity-dispersion increasing with age, etc) in the present author's opinion require its generalization towards a triaxial symmetry and a nonsteady state.

1. INTRODUCTION

As usually the notion "local" applied in galactic astronomy means something referred to the solar neighbourhood. Therefore, the Milky-Way local dynamics studies the dynamics of a small Milky-Way region near the Sun. The more abundant observational material existing for the solar-neighbourhood case compared to other parts of our Galaxy offers many questions for stellar dynamics to be answered. It was just the local kinematics which almost seventy years ago initiated the dynamical study of the galactic rotation. The basic ideas of this theory, as well known, are :

1. the steady state and axial symmetry of the Milky Way as a whole;
2. the ellipsoidal distribution of the residual velocities at the Sun for the disc stars.

These ideas have remained much unchanged. Therefore, the local dynamics of the Milky Way can be considered in two approaches - the classical one based on the two assumptions mentioned above and a more general one where the (inevitable) deviations from both steady state and axial symmetry are taken into account.

2. THE POSSIBILITIES OF THE CLASSICAL APPROACH

In the founding of the Milky-Way local dynamics one can choose different ways. In the present author's opinion the best one is, certainly, which introduces the notion of the dynamical constants (Ninković, 1987b). These are the local values of dynamical quantities, i. e. their values taken at the galactocentric position $R = R_\odot$, $Z = 0$. In the framework of the classical approach the constants of interest are : the local value of the potential, the first radial derivative ($\frac{\partial \Pi}{\partial R}$), the second radial derivative ($\frac{\partial^2 \Pi}{\partial R^2}$) and the second vertical derivative ($\frac{\partial^2 \Pi}{\partial Z^2}$) (in all cases their local values). Higher-order derivatives are not of interest and in the classical theory all other derivatives up to the second order are zero in the galactic plane.

It is clear that these four quantities are not directly determinable from the observational data, however the theory connects them with some other quantities easier to interpretation. The correspondence is the following

potential corresponds to escape velocity;
its first radial derivative to circular velocity;
its second radial derivative to circular-velocity slope;
its second vertical derivative to cyclical frequency of vertical oscillations.

The relations connecting these quantities are well known and there is no need to present them here. It is clear that there are also other quantities which can be used for the same purpose - for example, the local angular velocity of circular motion instead of the local circular velocity, then the pair local circular velocity and its slope can be substituted by the well-known Oort constants A and B (or more precisely by their dynamical counterparts), etc. The cyclical frequency of vertical oscillations is also known as Kuzmin's parameter, or constant, (C) (e. g. Einasto, 1974) forming thus a system of three dynamical constants.

As well known, the situation with all these values is not quite clear. The IAU recommended a value ($220\ km\ s^{-1}$) for the local circular velocity but without recommending any particular values for the Oort constants and also for the Kuzmin one (Kerr and Lynden-Bell, 1986); the escape velocity was not even treated in this report probably because it is least reliably known. In addition, the local-escape-velocity problem is not a local problem only, since this question involves the global dark-matter problem.

In spite of all these circumstances the present consideration shall include the local escape velocity. The recent increase of the observational material, above all towards high-velocity stars, has clearly shown that in the solar neighbourhood stars with galactocentric velocities as high as $450\ km\ s^{-1}$ are not rare and therefore this value was advocated as a correct one for the local escape velocity (e. g. Rohlfs and Kreitschmann, 1981). With regard that stars with even higher galactocentric velocities have been also found, it may be considered rather as a lower limit and somewhat higher values have been also proposed (e. g. Ninković, 1987a; Cudworth, 1990). However, in view of the extremely low number density of the stars with exceptionally high galactocentric velocities, the arguments pro et contra coming from studies of the global Milky-Way structure, aimed at answering the dark-matter question, must be also taken into account. Though, at first glance, it seemed that the motion of the Milky-Way satellites was not in favour of a high dark-matter content (e. g. Lynden-Bell et al., 1983), the gradually adventing more recent evidence, especially the case of Leo I(e. g. Lee et al., 1993), seems to suggest a very high Milky-Way total mass so that the prediction of Caldwell and Ostriker (1981) being in favour of a very high local escape velocity (550 - $650\ km\ s^{-1}$) seems justified. In any case the values of 500 - $700\ km\ s^{-1}$ for the local escape velocity clearly suggest that the total mass of the Milky Way significantly exceeds that of its seen matter.

As for the local circular velocity, the situation is certainly more clear than in the case of the local escape one. It could be noticed that the comparatively recent trend has been to correct its value downwards. The value mentioned above, recommended by the IAU ten years ago, is less than the previous IAU official value of 250 $km\ s^{-1}$ (assumed at the IAU General Assembly in Hamburg in 1964), but there are proposals in favour of even lower values(e. g. Rohlfs and Kreitschmann, 1987). This downwards correcting is frequently followed by a corresponding correcting of the solar galactocentric distance in the same sense so that the resulting changes in the local angular velocity of circular motion are smaller. However, since the first radial derivative of the potential, or the strength of the gravitational field (more precisely radial component, but note that the other one is zero in the plane), depends on both the circular velocity (corresponding angular velocity) and $R_\odot$, their changes will certainly affect its local value. The effect can be illustrated by the following examples : the old IAU official values yield 6250 $km^2\ s^{-2}\ kpc^{-1}$ for the local gravitational-field strength, those actually recommended by it yield about 5700 $km^2\ s^{-2}\ kpc^{-1}$. As extremal examples one may mention that for the same quantity the values proposed by Rohlfs and Kreitschmann (1987) yield about 4300 $km^2\ s^{-2}\ kpc^{-1}$, whereas those of Balázs (1982) yield about 8450 $km^2\ s^{-2}\ kpc^{-1}$!

The local circular-velocity slope can be determined through the ratio of the Oort constants. It can be also related to another dimensionless quantity - the dynamical coefficient γ being the ratio of the second radial derivative of the potential to the square of angular velocity of circular motion - introduced by the present author (Ninković, 1987b). The situation is not quite clear. The examinations of the neutral-hydrogen rotation suggest an approximately flat circular-velocity curve within a sufficiently wide galactocentric-distance range, including the solar region as well (e. g. Haud, 1979; Fich et al., 1989). Such a situation, as easy to see, corresponds to equal moduli of the Oort constants. However, many investigators find a slight decrease in the circular velocity near the Sun - for instance the straight unweighted means presented by Kerr and Lynden-Bell (1986 - Table 10 of their paper). It is interesting to note that such findings do not contradict to the general trend of a flat galactic rotation curve. A good example is, certainly, that of Rohlfs and Kreitschmann (1987) who though on the average find $A = -B$, nevertheless obtain for the solar neighbourhood such a ratio of the Oort-constants moduli which would correspond to a local circular-velocity decrease characteristic for the case of an almost point-mass gravitational field! Of course, one may wonder in what degree such a wavy circular-velocity curve is close to reality, perhaps a smoothing is necessary. Finally, it can be said that most likely the circular velocity in the solar neighbourhood is approximately constant with a tendency of slight decrease. With regard that the second radial derivative depends not on the circular-velocity slope only, i. e. on γ coefficient (Ninković, 1987b), but also on the square of the angular velocity of circular motion, it is useful to present its possible value. If assumed, following the IAU, that the local angular velocity is most likely equal to some 25-26 $km\ s^{-1}\ kpc^{-1}$, then in view of the said above the second radial derivative would lie somewhere between 600 $km^2\ s^{-2}\ kpc^{-2}$ and 800 $km^2\ s^{-2}\ kpc^{-2}$.

In addition, according to the classical theory the ratio of the mean residual-velocity squares along the axes directed to $l = 0°$, $b = 0°$ and $l = 90°$, $b = 0°$, denoted as $\overline{\dot{x}^2}$ and $\overline{\dot{y}^2}$, respectively, is determined by the Oort-constants-moduli ratio. For the case of the equal moduli the corresponding value of this ratio is 2. However, the local stellar kinematics suggests a higher value, usually about 2.56 (e. g. Kulikovskij, 1985, p. 86). Recently the present author (Ninković, 1992) offered a new solution by amending the classical formula with a new term containing the ratio of the asymmetric-drift square to $\overline{\dot{x}^2}$. It seems that with this correction an agreement can be achieved.

The situation with the Kuzmin-constant value seems to be the most unclear. It should be emphasized here that this constant is very important because by its contribution is essentially determined the local value of the potential laplasian, i. e. the local density of the galactic matter. This problem is very well known since long ago - so-called Oort's limit (Oort, 1965) - or the local dark-matter problem since many astronomers have found that this "dynamical" density significantly exceeds that following from stellar statistics. However, the problem seems still far from the solution. In Gliese's (1983) review the whole controversy of the problem was emphasized. Here it can be added that there seems to be something like a systematical tendency of some schools of stellar dynamics for preferring certain values. For example, there are several results of the Tartu astronomers where the values close to those found by means of stellar statistics were communicated (e. g. Einasto, 1974 and the references cited therein; Jõeveer and Einasto, 1976; Haud and Einasto, 1989; Eelsalu, 1990). On the other hand some Western-Europe astronomers have found several times values sufficiently exceeding the value derived from stellar statistics (e. g. Fuchs and Wielen, 1986; Crézé et al., 1989). In the astronomical circles of the Anglo-Saxon countries it seems as practically assumed that the local "dynamcal" density is approximately twice as high as the "statistical" one (e. g. Binney and Tremaine, 1987, p. 17; Freeman, 1987). The present author has also a result on the dynamical local-density determination (Ninković, 1987b) where a value quite close to the statistical one was found.

It is usually thought that this local dark-matter problem has nothing to do with the galactic dark corona because it is not sufficiently flattened (e. g. Binney et al., 1987; Trimble, 1987). For example, it has been demonstrated by the present author that unless the corona is as flattened as the axial ratio not exceeding 0.1, its contribution to the local galactic-matter density cannot be essential (Ninković, 1990).

In general it may be said that the values found dynamically for the local density and exceeding the double statistical value seem unrealistic. Thus, if the local dark-matter problem really exists, most likely the local dark-matter mass does not exceed that of the seen matter. On the other hand, since the local-circular-velocity determination does not indicate an essentially higher disc mass within the Sun, the disc dark matter, if it really exists, should be looked for near the galactic plane. Such a search has been already undertaken, even in the Solar System (e. g. Tremaine, 1990).

3. ELLIPSOIDAL DYNAMICS

The hypothesis of ellipsoidal velocity distribution for the disc stars in the solar neighbourhood is sufficiently well known. It is also well known that it is possible by using the Boltzmann equation to determine the galactic potential on the basis of the known phase-space density represented through the velocity ellipsoid (e. g. Chandrasekhar, 1960). It is interesting to mention that such potential determinations have not yielded a potential function depending on the space coordinates (above all R and Z) in a way sufficiently close to what, say, the rotation-curve determinations yield (e. g. Sanz, 1987; Sala, 1987; Sala, private communication). Thus one finds another example of discordance between the Milky-Way local dynamics and the global one.

As for this discordance, it is usually borne in mind the ratio of the mean velocity squares $\frac{\overline{\dot{x}^2}}{\overline{\dot{z}^2}}$. As well known, the classical theory of Lindblad yields the value of one for it due to the assumption of only two integrals of motion. Therefore, the discussion goes to another topic now - that of the third integral. As well known, several functions, largely quadratic in the velocity components, have been proposed as approximate integrals of motion (for more details e. g. Ogorodnikov, 1958, p. 296). The question has not been definitely solved yet. Most likely the third independent nonclassical integral of motion exists, but it is not clear in what way it restricts the motion of a test particle. For the case of the galactic disc (nearly circular motion) Lindblad's theory predicts a constant amplitude of the motion along the Z axis so that the part of space occupied by the test-particle orbit is limited vertically by two planes parallel to the main plane of the Milky Way. The calculations of the galactocentric orbits for some disc stars in realistic galactic potentials (e. g. Mullari et al., 1994) shows that the real situation is more complicated which is probably caused by the third-integral nature.

4. BEYOND THE CLASSICAL APPROACH

It is clear that the idea of the steady state and axial symmetry is merely an approximation. There are many phenomena which can be hardly explained in the framework of this hypothesis. The solar neighbourhood, on the other hand, offers for clear reasons many fine details where the deviations from the steady state and axial symmetry can be studied. Some of them should be mentioned : the vertex deviation, the Gould belt, etc. It should be added that the analysis through the Boltzmann equation with the ellipsoidal velocity distribution as working hypothesis is applicable to this case, as well. This can be seen, for instance, from the references cited in the next paragraph.

The vertex deviation is a well known phenomenon. It seems not difficult for explaining if the axial symmetry is generalized towards the triaxial one (e. g. Sanz Catala, 1987). However, it should not be forgotten that the vertex deviation is a characteristic of samples consisting of early-spectral-type stars, i. e. young ones. Therefore, one can ask why the triaxiality effect (if this is really the explanation) is selective against later-spectral-type stars. This circumstance justifies another way, i. e. to look for the explanation in the framework of a nonsteady state including the star formation still active in the disc. Various possibilities have been considered including also the superposition of two stellar systems (e. g. Sanz et al., 1989; Cubarsí, 1990).

In favour of the deviations from the steady state is also the following circumstance. Namely, it has been noticed that the mean squares of the residual-velocity components for the disc samples consisting of younger stars are lower than in the case of the so-called old disc (e. g. Mayor, 1974; Carlberg et al., 1985). This effect seems to be well established in spite of a quantitative disagreement (Freeman's comment - Freeman, 1987). It is possible that the velocity-dispersion increase in the z direction is stronger than in the other two, a phenomenon probably in favour of a nonsteady state. A possible explanation may be some kind of galactic diffusion (e. g. Wielen, 1977). It is also not impossible that the phenomenon is due to another mechanism important for our Galaxy, such as the spiral density waves (e. g. Balázs, 1982) moving groups (e. g. Eggen, 1986), etc.

5. CONCLUSION

Certainly, the most important conclusion may be that the field of the Milky-Way local dynamics, though sufficiently treated in the past, still offers many tasks for research. During the recent two decades an undoubted progress concerning the local escape velocity was achieved, but on the other hand some old questions, such as the ratio of the Oort constants, the amount of the Kuzmin one, etc, seem to become actual again after a period when they were thought to be known satisfactorily well. As quite clear appears that the interpretation of the phenomena discordant with the steady state and axial symmetry requires most of the efforts.

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