# KINEMATICS AND DYNAMICS OF THE MAGELLANIC CLOUDS

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## 1. INTRODUCTION

Why are the kinematics and dynamics of the Magellanic Clouds worth studying ? Some of the reasons are:

1. The Clouds are the closest examples of Magellanic systems. These asymmetric systems give some interesting dynamical problems. Because the Clouds are so close, a unique amount of information can be obtained on the kinematics of objects of all ages. This should be very helpful for understanding the dynamics.

2. The Clouds and the Galaxy are interacting. This produces complex kinematics of the gas in and between the Clouds, and also the Magellanic Stream. Again, very detailed information can be derived. We would like to know enough about the gas dynamics of interacting galaxies, to be able to explain the kinematics produced by this interaction.

3. The interaction will affect the star formation and chemical evolution in the Clouds. As new results are obtained on the star formation history and the chemical evolution, it is important to follow in parallel the dynamical history of the system, to see if the dynamics, star formation and chemical evolution can be tied together.

New results on the HI kinematics of the LMC and SMC, and on the dynamics of the interaction, have been reviewed by others. I will concentrate mainly on the dynamics of individual Magellanic systems, with particular application to the LMC and SMC. I will also discuss some new results on the kinematics of the globular cluster system of the LMC; this is interesting, because it includes objects of all ages.

## 2. STRUCTURE AND DYNAMICS OF MAGELLANIC SYSTEMS

For detailed reviews, see de Vaucouleurs and Freeman (1973: dVF) and Feitzinger (1980: JF). These reviews include photographs and



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diagrams to illustrate many of the points made below.

2.1 Basic Structural properties

Magellanic systems frequently come in pairs. The LMC/SMC is just one example. NGC 4618/25 and NGC 4027/4027A are among others that are strikingly similar to the LMC/SMC in their appearance and gross properties. This supports the view that the LMC/SMC is probably a relatively longlived binary pair.

The basic structure shared by these barred Magellanic systems is the strong asymmetry of the spiral structure about the bar axis. The bar appears displaced from the center of the outer isophotes. In this respect, the SBm systems are analogous to the "lopsided" normal spirals like M101, in which the spiral structure appears very asymmetric about the nucleus. (See Baldwin et al. (1980) for a recent discussion.)

This largescale asymmetry is seen also in the rotation curves. The LMC, NGC 4027 and NGC 55 are just a few examples in which the center of the rotation curve is displaced from the center of the bar by several hundred parsecs. JF has compiled data on the displacement of the bar from the isophotal center and from the rotation center, for a sample of Magellanic systems. The two displacements are indeed very similar.

2.2 Intrinsic Flattening

It seems clear from their appearance and rotation that the Magellanic systems are disklike. Surface photometry shows that their disks have the exponential surface brightness distribution that is so characteristic for disk galaxies of all types. The intrinsic flattening of the Magellanic systems is particularly interesting. Heidmann et al (1972) showed how the intrinsic flattening of disk galaxies increases monotonically from SO to Sd, where it takes a maximum value (major to minor axis ratio) of about 12. From Sd towards later types, the intrinsic flattening then decreases abruptly, to about 6 at Sm and 5 at Im.

Why should the Magellanic systems be so much less flat than the Sd spirals ? The reason may have to do with the asymmetry described above, which begins to appear at stage Sd. The intrinsic flattening is the ratio of the isophotal major to minor axis for an edge-on system. The major axis is determined mainly by the galaxy's exponential lengthscale, which in turn is closely correlated with its absolute magnitude. The minor axis, for these late-type pure disk (ie almost bulgeless) galaxies, is defined by the thickness of the disk, which in turn is determined mainly by disk heating processes. These disk heating processes are not yet fully understood (see for example the review by Wielen and Fuchs, 1984). In particular, the primary heating mechanism remains uncertain. However, in the asymmetric Magellanic systems, the asymmetry itself provides another source of disk heating, through the resonant excitation of motion perpendicular to the galactic plane (Binney 1981). This mechanism acts in addition to the heating processes that operate in the more symmetric disks, and it could explain why the Magellanic systems are less flat.

It would be interesting to make a study of the vertical (z) structure of Magellanic systems. Do they show the characteristic $\mathrm{sech}^2(z/z_o)$ density profile seen in earlier type spirals (van der Kruit and Searle 1982) ? What vertical structure would we expect if the resonant heating by the asymmetry is the dominant mechanism for heating the Magellanic disks ? The large amount of kinematical information that can in principle be obtained for stars of all ages in the LMC would be very useful for understanding the time-dependent vertical structure of Magellanic systems.

## 2.3 Dynamical Studies of Isolated Magellanic Systems

Not much work has been done so far on the dynamics of these asymmetric galaxies, so the subject is in a fairly primitive state. The early work was reviewed by dVF, and we will just summarise it briefly here. The purpose of these dynamical models was to explain the structural properties of Magellanic systems (the asymmetric spiral structure and rotation curves, and the wave observed in the rotation curve of NGC 4027: see dVF for details). The first step was to adopt a background gravitational potential. This potential should include the basic features of SBm systems which distinguish them from the more symmetric barred galaxies. A typical SBm system has an exponential disk, which provides most of the light, and a small bar. However the centers $C_b$ of the bar and $C_d$ of the disk do not coincide, but are separated by a distance $\Lambda$ which is typically between 0.5 and 1 kpc. To represent this asymmetrical situation in a simple time-independent way, Freeman and Harrington (1968: see also dVF) introduced a potential based on Figure 1a. The bar rotates around the center of the disk, such that the line $C_dC_b$ is always normal to the major axis of the bar. The potential field for this model is shown in Figure 1b. For parameters appropriate to SBm systems, the total potential (gravitational + centrifugal) has one stable neutral point $M_5$ and one unstable neutral point $M_4$. The stable neutral point $M_5$ acts to trap matter circulating around it. Christiansen and Jefferys (1976) used this potential in a particle orbit study of the SBdm galaxy NGC 4027. They were able to explain the large wave observed in the rotation curve of this galaxy: it results from the trapping and circulation of particles around $M_5$.

The particle orbit work is only a first step. A proper hydrodynamical treatment of the gas response and motions in this Magellanic potential is needed. Colin and Athanassoula (1983) have presented a preliminary report of such a study, which shows how a stationary gas response develops.

## 2.4 The LMC-SMC-Galaxy Interaction

The dynamics of isolated SBm systems need to be understood but, on their own, will not help us to understand the complex kinematics in the

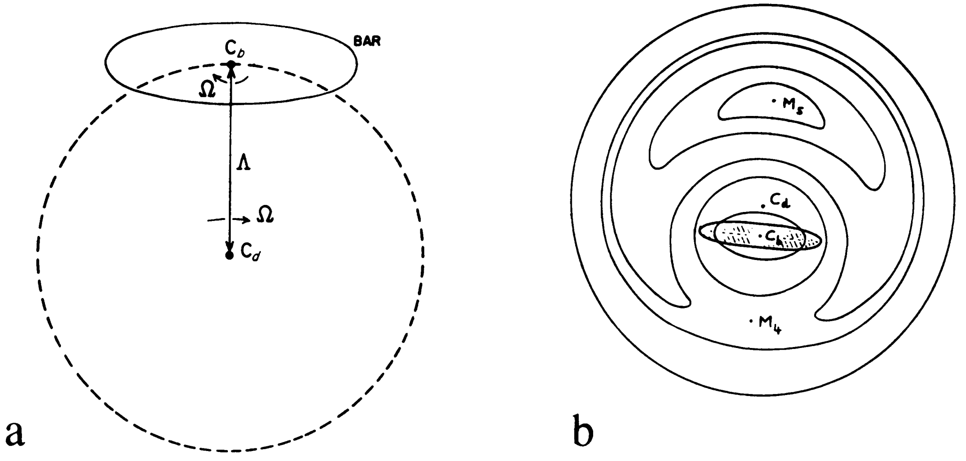


Figure 1a. Motion of the bar relative to the disk center $C_d$ in the SBm model. The broken circle is the orbit of the bar center around $C_d$.
Figure 1b. Equipotentials of the gravitational + centrifugal potential for the model of Figure 1a, with typical parameters (see dVF). $M_4$ and $M_5$ are the neutral points.

LMC and SMC, except perhaps in the innermost parts of the LMC. The problem is, of course, that the LMC/SMC is apparently an interacting binary system which is also interacting with the Galaxy. Observationally there seems no doubt about the important influence of the LMC-SMC-Galaxy interaction on the HI kinematics. Mathewson et al (1979) showed that the velocity field of the HI between the Clouds has a very regular structure. The "isovels" are approximately parallel to the LMC-SMC line, in the region between the Clouds and also to the West of the SMC and the East of the LMC. The disturbing effect of the LMC's rotation on this pan-Magellanic velocity field can be seen in the isovels, but only within about 5 degrees of the LMC's rotation center.

The HI structure and kinematics of the LMC and SMC are discussed in the contributions by Feitzinger, Kreitschmann and Rohlfs, and by Mathewson and Ford, in this volume. However it seems clear that the motions of the HI in the outer parts of the LMC, and over much of the SMC, will be significantly affected by the pan-Magellanic flow field. This makes it very difficult to derive a reliable circular velocity curve and velocity field for the LMC itself, except within a few degrees of the rotation center. In particular, there seems to be no immediate hope of determining from the kinematics whether or not the LMC has a massive dark corona.

For the SMC, the situation is even more difficult. The SMC has an absolute blue magnitude of -16.2, so we expect from the Tully-Fisher

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relation a maximum rotational velocity of about 35 km $s^{-1}$. This small rotation would be almost lost in the pan-Magellanic velocity field of Mathewson et al. (1979).

If this direct observational evidence for the effects of the interaction is not enough, recent theoretical work shows how large these kinematical disturbances are expected to be. For example, Murai and Fujimoto (1980) made a study of the dynamics of the LMC and SMC orbiting around a model Galaxy with a massive halo. They showed how the Magellanic stream results, in their model, from SMC material torn off by the tidal force of the LMC. SMC material also forms a bridge between the SMC and the LMC. The interaction produces velocities that are comparable with those observed by Mathewson et al. (1979).

Again, a hydrodynamical treatment of the motion of gas in the interacting system would be valuable. However there is still some disagreement about the orbit of the LMC/SMC around the Galaxy: even the sense of rotation of the orbit is still in dispute (see for example Tanaka 1981).

There seems no way that we can give a good dynamical description of the LMC and SMC until the effects of the LMC-SMC-Galaxy interaction are properly understood. This must be a top priority item for dynamical studies of the LMC and SMC. The LMC/SMC pair is not the only example of interacting Magellanic systems. Weliachew et al. (1978) made an HI study of the interacting pair NGC 4631/NGC 4656, and Combe (1978) was able to make a successful dynamical model for the gas motions and distribution in this system.

## 2.5 Dark Matter in Magellanic Systems

Although it will not be easy to determine whether the LMC and SMC have massive dark coronas, some progress has been made for the more isolated Magellanic system NGC 3109. This system lies between the LMC and SMC in absolute magnitude: $M_B$ = -16.2, -17.3, -18.2 for the SMC, LMC and NGC 3109 respectively. Carignan (1983) has made surface photometry for this galaxy and, in a combined Fabry-Perot and 21-cm study, has measured its rotation curve to a radius of about 10 kpc. The rotation curve continues to rise, to about 60 km $s^{-1}$. Carignan calculated the rotation curve to be expected, if the mass distribution follows the light distribution (Kalnajs 1983). This expected rotation curve fits well in the inner 2 kpc, but then drops rapidly. To fit the rotation data, Carignan required, in addition, a massive dark corona (isothermal sphere) with a core radius of 3.3 kpc and a velocity dispersion of 45 km $s^{-1}$. Within 10 kpc, this dark corona is 7 times more massive than the luminous disk. NGC 3109 is one of the most unambiguous examples of a galactic dark corona: it suggests that other Magellanic systems, like the LMC and SMC, may be similarly endowed.

## 3. KINEMATICS OF THE GLOBULAR CLUSTERS OF THE LMC

Most of the information about the kinematics of the LMC and SMC comes from the extreme population I (HI, young stars, HII region) which, as suggested above, may be kinematically affected by recent events in the LMC-SMC-Galaxy interaction. A recent study by Freeman et al (1983) compares the kinematics of LMC globular clusters of all ages. (This study owes much to Drs Cowley Hartwick Searle and Smith, who allowed us to use their data before publication.) We made rotation solutions for young clusters and old clusters separately. Because the total number of clusters with good velocities was only 59, we did not attempt to derive the rotation curve: rather, we assumed that it was flat, and solved for the rotation velocity $V_m$, the systemic velocity $V_o$ (relative to the galactic center), the position angle $\theta_o$ of the line of nodes, and the dispersion $\sigma$ about the rotation solution. The results are summarised in the table below. The age groups are similar to those defined by Searle et al (1980). All velocities are in km $s^{-1}$.

| Group | Age | N | pa($\theta_o$) | $V_m$(rot) | $V_o$(sys) | $\sigma$ |
|---|---|---|---|---|---|---|
| I-III | < $3.10^8$ y | 24 | 1 ± 5 | 37 ± 5 | 40 ± 3 | 15 |
| IV-VII | $3.10^8$->$10^{10}$ | 33 | 41 ± 5 | 37 ± 3 | 27 ± 2 | 17 |
| VII | > $10^{10}$ | 9 | 44 ± 6 | 54 ± 7 | 38 ± 4 | 16 |

The solution for the young clusters is fairly similar in position angle, rotational velocity and systemic velocity to the solutions for the HI and HII components (see JF). It seems clear that the young clusters are moving with the gas from which they recently formed. The older clusters are also apparently in a disklike distribution, with a similar rotation amplitude and an intrinsic velocity dispersion of only 17 km $s^{-1}$. (This small dispersion was noted by JF, and corresponds to a vertical scale height of only 600 pc). However the position angle for the old cluster line of nodes is very different ($41^o$) from the position angle for the young clusters ($1^o$). We see from the table that even the oldest clusters (group VII) appear as part of the same old disk; their dispersion is only 16 km $s^{-1}$, so there is no evidence for a kinematic halo population among the globular clusters of the LMC.

Why should the position angles of the old cluster and young cluster disks be so different ? (This difference remains in solutions that include a transverse motion of 300 km $s^{-1}$ for the LMC). We suggest that the old clusters delineate the true old disk of the LMC, while the kinematics of the young clusters and the gas have again been affected by recent events in the interaction of the LMC-SMC-Galaxy system. This view is supported by the recent HI study of the LMC by Feitzinger et al (this conference); they find a position angle of about $28^o$ for the HI in the inner few degrees of the LMC, where the effects of the interaction would be least. Qualitatively, it fits in with the interaction picture of Murai and Fujimoto (1980). They find that the LMC and SMC suffered a close approach about $2.10^8$ y ago, with a 3 kpc separation of the two systems; this is by far the closest approach in the entire history of the interaction. If their interaction picture is correct in concept, then this recent severe interaction is presumably the one responsible for the disturbed state of the gas kinematics in the LMC (see JF for details). We might then expect that the young cluster system (ages less than $3.10^8$ y) will reflect the disturbed kinematics of the gas from which it formed, while the kinematics of the older cluster system reflect the more sedate dynamical history of the period before this recent close approach.

This recent close encounter fits well also with the evidence by Frogel and Blanco (preprint) for an epoch of enhanced star formation at a time corresponding to the age of the young clusters. We recall the suggestion by Gunn (1980) that the young clusters themselves (which have no counterparts in the Galaxy) formed in a shock-induced star formation episode excited by recent interaction between the two Magellanic Clouds.

It would be worth studying the kinematics of other LMC objects that cover a wide range of ages, to find out if the kinematical effects shown by the old and young clusters are seen again. Planetary nebulae are such objects: however their kinematics do not conform to either of the cluster solutions, young or old. More work would be welcome here. Bessell, Wood and I have begun a kinematical study of the LMC long period variables, which again straddle the relevant age range.

## 4. SUMMARY

1. For the dynamics, the important property of Magellanic systems is their structural and rotational asymmetry.

2. Magellanic systems are significantly less flat than Sd galaxies. This may be due to disk heating associated with the largescale asymmetry.

3. The effects of the LMC-SMC-Galaxy interaction need to be properly understood before much progress can be made on the dynamics of the individual Magellanic Clouds.

4. At least one Magellanic system, NGC 3109, shows very compelling evidence for a dark massive corona.

5. Both the young and the old globular clusters of the LMC lie in kinematically defined rotating disks. However the two disks have very different lines of nodes. We suggest that the old clusters represent the true old disk of the LMC, and that the kinematics of the young clusters and the gas are affected by the LMC-SMC-Galaxy interaction. There is no evidence for a kinematical halo population in the LMC.

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DISCUSSION

**Walborn:** You showed some interesting cases of pairs of asymmetrical irregulars, but also similar asymmetries in apparently single objects. Are the observed spatial structures of the Magellanic Clouds believed to be due to mutual interaction?

**Freeman:** No. There are many examples of relatively isolated Magellanic systems. I was just trying to say that pairs of Magellanic galaxies, like the LMC/SMC are not rare.

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