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Final Technical Report

THEORETICAL PROBLEMS OF SPIRAL GALAXIES

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FINAL REPORT TO NASA

ON

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I. Introduction

Three theoretical problems concerning the large-scale structure of disk galaxies in general, and the Milky Way System, in particular, were proposed to study. They are, namely, (1) modes of spiral density waves, (2) evolutionary change of the abundance distribution of the gas in the Milky Way System and (3) the motions of the cloud medium behind the large-scale galactic shock. In conclusion, the proposed research can only be considered half finished.

To calculate spiral modes of density waves for galaxies of the type of the Milky Way System, as it turns out, requires more times and manpower than what I could afford in the capable of a full time university professor. There were no qualified advanced graduate students avaialble at the time. Only preliminary computations were carried out to put the problem into a comprehensive matrix form and no serious attempt was made to find the eigenvalues of this highy non-linear algebraic system.

The attempt to calculate the evolutionary change of the gas distribution due to the depletion of the gas to star formation in spiral galaxies has yielded some useful results. But, the mechanism simply can not generate any large-scale radial streaming motion even at the location of the inner Lindblad resonance. Thus, it can not induce the fast expansion motion of the gas, known as the "3-kpc" arm. However, this study has inspired us as well as equipped us with the right device to consider other alternatives, which prove to be extremely promising lately. All of these are described in Section II.

The motions of the cloud medium behind a large-scale galactic shock were successfully computed. The results were published in Astrophysical Journal. We have shown that the collision among individual clouds is the mechanism responsible of slowing down the cloud medium, not the drag face between individual clouds and the intercloud medium. The results and the followup work are persented in Section III.

During the course of study, other theoretical problems related to the large-scale structure of the Milky Way System, which had been considered slightly before the grant period, or were added during the period, were also completed. One paper on the theoretical surface photometry; one on the local standard of rest and one on the vertical structure of the large-scale galactic shock were published. All of them are closely related to the study of the motion's of the cloud medium. A summary of them is given in Section IV.

II. Evolution of the Large-scale Gas Distribution

A one-dimensional numerical gasdynamical code is constructed to calculate the radial motion of the gas, induced by the depletion of the gas to star formation, which, in turn, results in unbalanced pressure gradient. The evolutionary change of the gas distribution at a given rate, which is taken to be proportional to the number of passages of the gas through a spiral shock (Oort 1974), is shown in Figure 1. We assume that the star formation is mainly caused by the galactic shock and young stars therefore are formed along the spiral arms. Inside the inner Lindblad resonance ($\sim$4 kpc for the Milky Way), spiral structure ceases to exist, there the rate of star formation is zero. Immediately outside the inner Lindblad resonance, the rate of star formation reaches its maximum because the number of the passages through shocks is the highest. One therefore would anticipate that a sharp pressure gradient will be set up in the course of time and hence will induce large radial motions. This turns out not to be the case. The gravitational field of the Galaxy is a few orders of magnitude higher than the force of the pressure gradient. Unless a mathematical discontinuity actually occurs, which is neither physically nor numerically possible, a small radial displacement of the gas will be sufficient to take care of the sharp pressure gradient. In Figure 1, we have calculated the gas density in reverse of time, i.e., taking the present data and tracing the initial distribution backward in time. The density distributions have sharp changes at the resonance region. But no significant radial flow is generated.

This result has important physical implications: (1) If stars are mainly formed outside the inner Lindblad resonance, the "hole" in the central region for the gas is far more severe than it is now. What has driven the gas out?. (2) Since the galactic gravitational field is so power in holding any odd distribution in the gas, what mechanism is responsible for the re-distribution of the gas in the long period of time after the disk is formed? A simple answer is the angular momentum. How the gas manages to acquire angular momentum is the central issue of the problem.

With the one-dimensional gasdynamic code, we study the gas motions in response to an axisymmetric periodic forcing. The magnitude of the forcing is small, usually a few percent of the local mean gravitational field. The frequency is taken to be the same value of the epicyclic frequency at the inner Lindblad resonance. The calculation is to simulate, in a simpler manner, the gas motions driven by a fast rotating bar or oval distortion in the center of the galaxy. Indeed, outgoing waves are excited at the resonance. The waves propagate outward at a phase velocity typically 40 km/sec. What is more remarkable is that the material velocity associated with the wave crest can reach up to 50 km/sec depending on the imposed field. A time-dependent solution is depicted in Figure 2. The results of this study are being prepared for publication.

Encouraged by these results, I start to examine the two-dimensional problem and find that the property of these waves can be understod by the linear theory. The linear wave is governed by an inhomogeneous Klein-Gordon equation. The waves are generated at the Lindblad resonance, which corresponds to a turning point mathematically so the wave solution exists only on the outer parts of the resonance while the solution decays rapidly on the other side of the resonance. The linear theory, however, has its limitation. It is not possible to have a radial velocity of 53 km/sec (the observed value) without violating the linear assumption.

It is fair to say that this research has opened up many new areas of research. The results here may be used as bases for (1) studying the two-dimensional non-linear theory which will answer the problem of the 3-kpc arm quantitatively, (2) giving possible solution to the angular momentum transfer problem of the solar nebula, if we believe a triaxial star was formed out of the initial condensation, (3) explaining the spiral structure in barred galaxies.

III. Motions of the Cloud Medium Behind the Large-scale Galactic Shocks

The results of this study are published in Astrophysical Journal (1982, see the Appendix). They may be summarized as follows: The rapid deceleration of the cloud medium behind the galactic shocks, as suggested by the observations, is mainly due to the process of cloud-cloud collisions. The shock-like structure of the cloud medium may be understood by assigning a turbulent viscosity to the cloud medium, equal to the product of the random velocity of the clouds and the mean-free-path of cloud-cloud collisions. The thickness of the shock is of the order of 100 pc, which is preceded by a thinner layer of 20 pc for the phase transition and thermal relaxation. The drag force between the clouds and the intercloud medium only plays a negligible role, Since cloud-cloud collisions are so important behind the large-scale shock, it must be directly related to the star formation which dominates the scene along spiral arms. This prompts us to consider the problem of the collision between two clouds and its possible relation to the star formation. On sabbatical leave from City College of New York as a National Research Council senior research associate, I am presently engaged in the study of this problem. The one-dimensional gas dynamic code developed for studying the large-scale gas motions (Section II) is expanded to a two-dimensional code. It is my hope that collision between two molecular clouds at moderate approaching speed may lead to effective star formation in the interstellar cloud.

IV. Other Related Publications

Three papers were also published during the grant period. All of them are along the same research line of Section III. Some of them (papers 1 and 2) were initiated slightly earlier but completed in the grant period, whereas the other (paper 3) was done entirely within the grant period.

(1) Surface Photometry of Spiral Galaxies I. Theoretical Color Variation and Surface Brightness Across Spiral Arms (with Preben Gerosbol Ap. J. 1981)

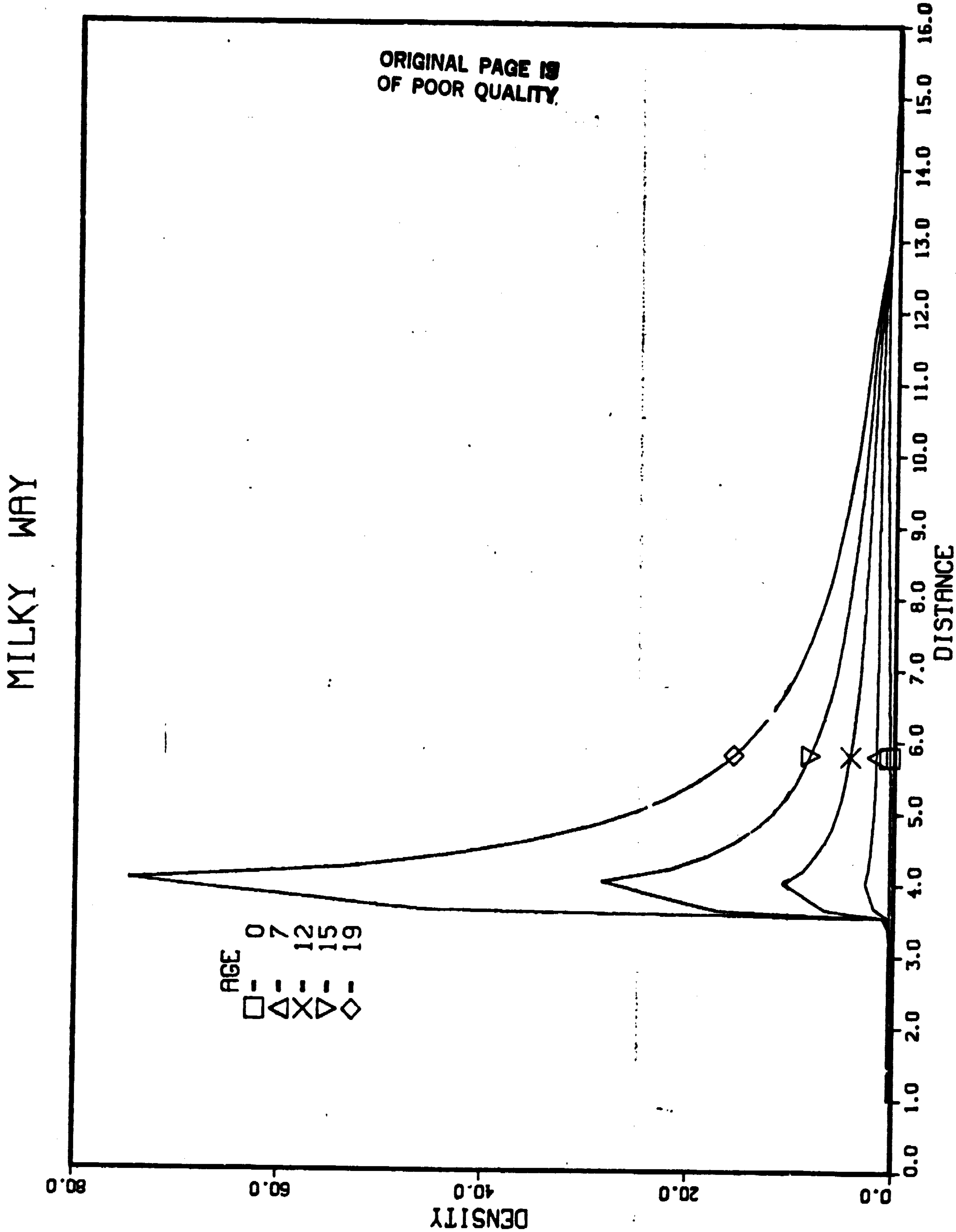
(2) Vertical Structure of Galactic Shock (with Judy Soukup, Ap. J. 1981)

(3) On the Local Standard of Rest (in Kinematics, Dynamics and Structure of the Milky Way, Ed. W. Shutter, D. Reidel Publications, 1982).

Captions of Figures

Figure 1 Evolutionary change of the gas density distribution at a given star formation rate proportional to the number of passages through spiral arms. The abscissa is the galacto-centric distance, and the ordinate is the density. The ages are in billion years.

Figure 2 The time-dependent response of the gas to an axisymmetric period forcing. The time advances towards upper right. The resonance is located at 3 kpc.


MILKY WAY
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△ - 7
X - 12
▷ - 15
◇ - 19
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60.0
80.0
DISTANCE
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2.0
3.0
4.0
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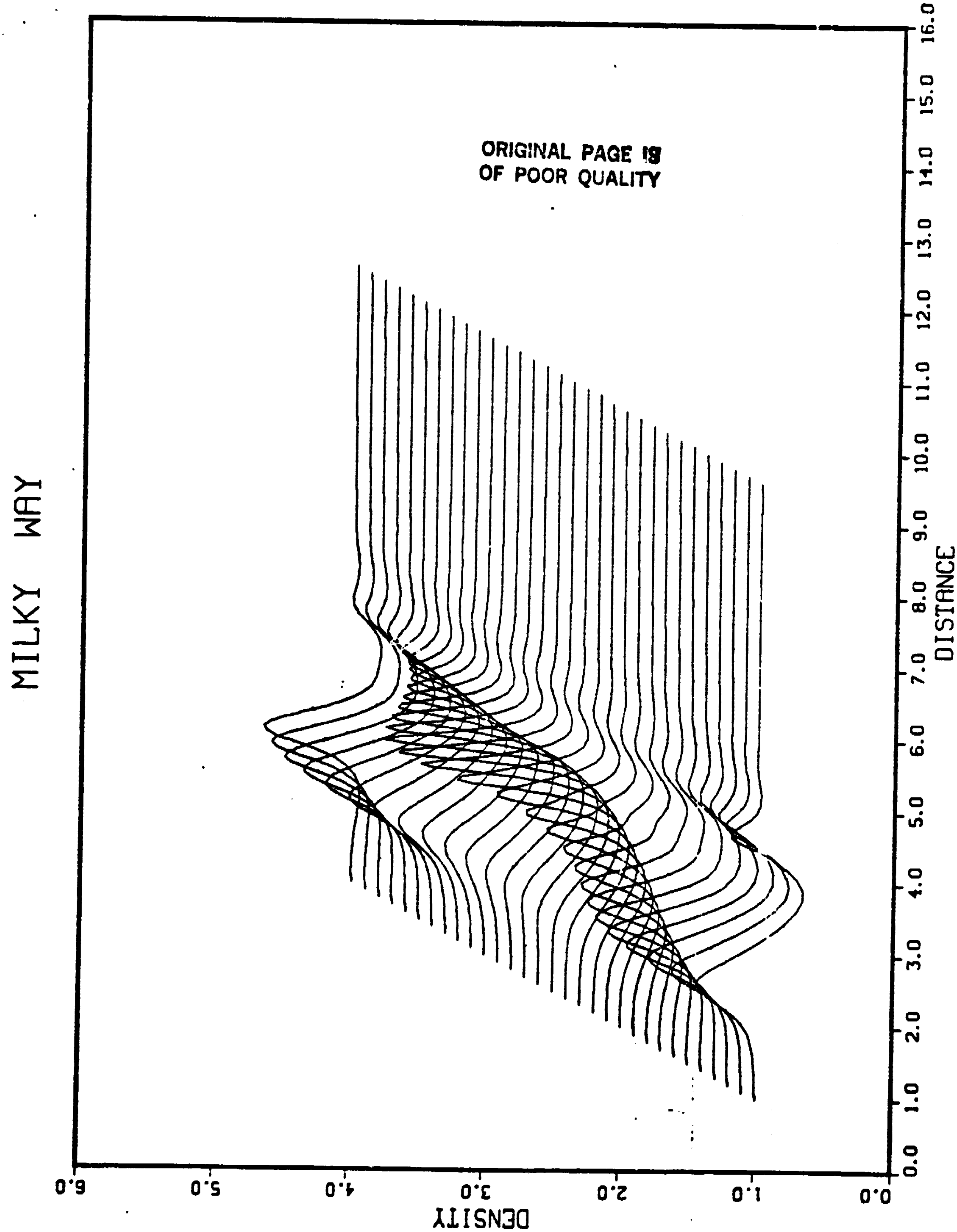
MILKY WAY
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DENSITY
0.0 1.0 2.0 3.0 4.0 5.0 6.0

APPENDIX

Reprints of Papers