# III. SPIRAL STRUCTURE

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# THE DENSITY-WAVE THEORY CONFRONTED BY OBSERVATIONS

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## 1. INTRODUCTION

Density waves are probably the most general phenomenon producing spiral structure in disk galaxies. The density-wave theory is able to give a rather successful interpretation of the observed spiral structure and of the related kinematics in external galaxies and in our Galaxy. We assume that the reader is familiar with the basic concepts of density-wave theory; for recent reviews see e.g. Kalnajs (1978), Lin (1975), Lindblad (1974), Marochnik and Suchkov (1974), Roberts (1977a,b), Rohlfs (1977, 1978), Shu (1973), Toomre (1977), Wielen (1974a). In Section 2, we discuss the proper theoretical devices which should be used for a meaningful comparison between observations and density-wave theory. The other sections are devoted to a comparison of density-wave theory with some relevant observations, mainly in our Galaxy.

## 2. HOW TO APPLY DENSITY-WAVE THEORY

Although the basic concepts of density-wave theory are rather simple, the predicted behaviour of well-observable objects such as HI, HII or young stars, turn out to be quite complicated. Unfortunately, some authors ignore these complications and try to fit the observations with oversimplyfied theoretical models. Obviously, such comparisons are of doubtful significance for an appraisal of the density-wave theory, although they may be sometimes justified for getting a first rough insight into the general capabilities of the theory.

### 2.1. Stationary density waves

It is generally assumed that the basic spiral structure of galaxies is of a rather permanent nature. Therefore, the density- wave theory assumes primarily a <u>stationary</u> wave in the gravitational potential of a galaxy. In the 'response problem', it is then asked how various populations of objects react on that potential wave. It is of primary importance to keep in mind that the conventional response formulae of the



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density-wave theory are only valid if the objects under consideration have already reached a stationary dynamical equilibrium in the galaxy. For reaching such a stationary state, typical objects require a few orbital revolutions in the galaxy. Hence only older stars, of an age of more than a few $10^8$ years, and the long-lived components of the interstellar gas can be described by the usual response formalism of the density-wave theory. In contrast to the older stars and to HI, no stationary density wave exists among younger stars or HII regions, because these objects have not had enough time to reach a stationary equilibrium state. Therefore, the usual formulae of the density-wave theory unfortunately do not apply at all to these well-observed young objects. The distribution and kinematics of young objects do not represent a wave phenomenon but can mainly be characterized as a migration out of the original spiral arms in which they were born. In order to predict the behaviour of young objects, we have essentially to solve an initial value problem for their orbits (Section 2.3.).

## 2.2. Linear theory and shock waves

At first, the linear version of the density-wave theory was developed by Lin and Shu. Later, it was shown by Roberts (1969), Shu et al. (1973) and Woodward (1975) that under rather general circumstances the interstellar gas reacts in a very non-linear way, including shocks, on even a small wave in the potential. In Fig. 1, we compare the surface density $\sigma$ and the velocities U and V of HI according to the shock version with the linear theory. The shock version is calculated for a 'standard' density wave in our Galaxy (e.g. Wielen 1973) at $R \sim 10$ kpc. While the phase and the relative amplitudes of the linear waves are provided by the theory, the absolute amplitude has been chosen freely to match as far as possible the velocities of the shock version. From Fig. 1 it is very obvious that the linear theory is not able to describe the behaviour of the gas properly, not even in a first approximation. Hence today, only the shock version should be used for a realistic discussion of the distribution and kinematics of HI. Additional uncertainties enter here, however, because of magnetic fields, different phases of the gas, etc. .

## 2.3. Motions of young objects

Star formation is probably very effectively triggered by the sudden increase in gas pressure at the shock front. Hence the birthplaces of most young objects should be close to the shock front. It is more difficult to derive the initial velocities of newly born stars. We may distinguish two plausible alternatives: In the post-shock case, the stars reflect the motion of the gas immediately after the shock. In the pre-shock case, the average initial velocity of a star is the gas velocity before the shock. If dense interstellar clouds do exist all the time, the pre-shock case would be adequate, because the motion of such clouds is not immediately affected by the shock front. If dense clouds are only formed after the shock front by phase transition, then the post-shock case would be appropriate. From the birthplaces and initial velocities, we can obtain the orbits of the stars in the $\Omega_p$-system which corotates with the

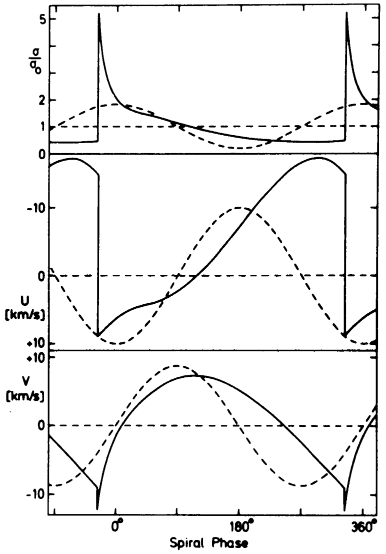


Figure 1. The surface density σ and the velocity components U and V of HI along a streamline. σ is normalized to its mean value $\sigma_0$. The U-axis points towards the galactic center, the V-axis in the direction of galactic rotation. The velocities are measured relative to the circular velocity at the actual position of the particle. Solid curve: shock version. Dashed curve: linear theory. The spiral phase of the density wave is zero at the minimum of the potential and increases by 360° from one spiral arm to the next one.

density wave (Fig.2) and the U- and V-velocities along the orbits (Fig.3) for a typical pre- and post-shock case (Schwerdtfeger 1977; Wielen 1975a, b, 1978). In Fig.3, the spiral phase indicates the position relative to the spiral potential. From the orbits of many test stars, we obtain in Figs.4 and 5 the drift of ageing spiral arms (defined by the locations of stars of a common age τ). The broadening of ageing spiral arms due to an initial velocity dispersion (10 km/s in the figures) is indicated by a cloud of stars. Figs.4 and 5 show that the drift and broadening are neither linear nor monotonic with age τ. From Figs.2-5, we must conclude that the motions of young stars are rather complicated, both in position and velocity space. They depend also on additional assumptions about star formation (e.g. pre- or post-shock case) which do not form an integral part of density-wave theory. All this hampers severely any conclusive comparison between theory and observations for younger stars and HII regions.

## 3. EXTERNAL GALAXIES

The general questions of existence, origin and maintenance of density waves should be studied mainly in external galaxies, where one can distinguish large-scale structure from local perturbations much better than in our Galaxy. In fact, external galaxies now provide the best evidence for the existence of density waves. Visser (1978) gives a very convincing interpretation of the Westerbork HI observations of M81 in terms of density-wave theory. The radio continuum observations of M51 (Mathewson et al. 1972) represent still the most suggestive evidence for the existence of spiral shock fronts (see also van der Kruit and Allen 1976). Optical observations of spiral galaxies (Schweizer 1976) can be interpreted

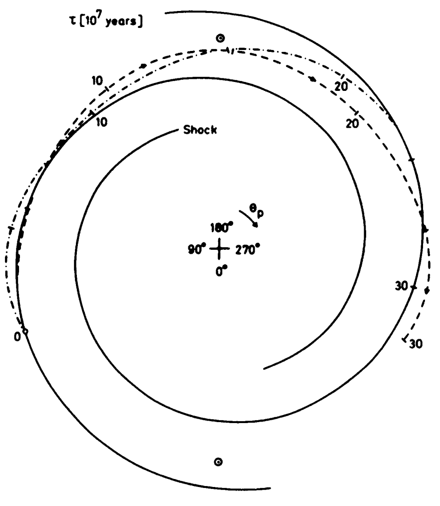

Figure 2. Typical pre-shock (dash-dotted) and post-shock (dashed) orbits of stars in the $\Omega_p$-system. The shock fronts are given by the solid spirals.

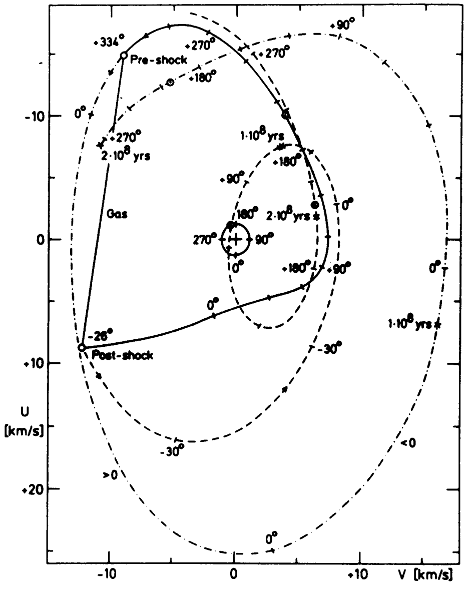

Figure 3. Velocities along the streamline of the gas (large solid curve), along the pre-shock orbit (dash-dotted) and along the post-shock orbit (dashed).

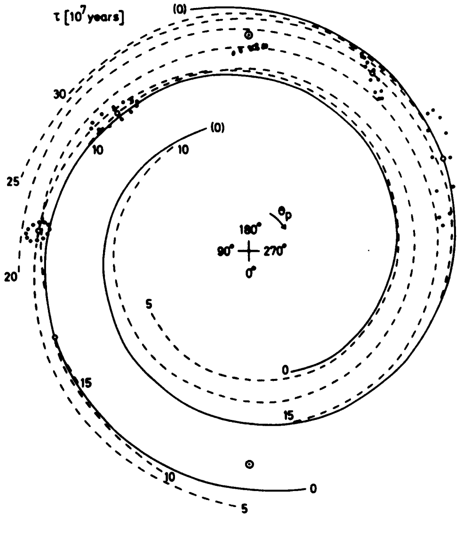

Figure 4. Drift of young stars of age τ for the pre-shock case.

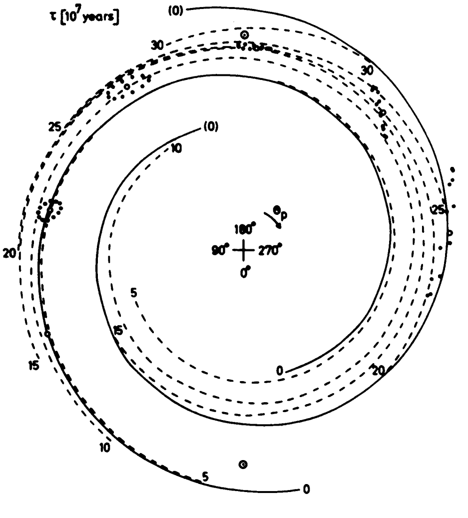

Figure 5. Drift of young stars of age τ for the post-shock case.

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as showing directly the basic density wave among the older disk stars, although the implied amplitudes of some of the waves are disturbingly high. It should be emphasized that the well-observed galaxy M33 has probably only a weak density wave without a significant shock front (Roberts et al. 1975), and is therefore less suited for a confrontation with theory.

## 4. OBSERVATIONS IN OUR GALAXY

### 4.1. HI

In our Galaxy, the best evidence for a density wave are still the wavy irregularities in the extreme radial velocities of HI at different galactic longitudes (Fig.6). The waves correspond to amplitudes in the tangential streaming velocity of HI of about 10 km/s. No conclusive quantitative confrontation of the observations with the shock version has been presented so far. Either the inappropriate linear theory has been used, or it has been incorrectly assumed that the V-velocity (Fig.1) at the tangential point is equal to the terminal velocity along the line of sight. For a correct procedure see Sawa (1978). It is rather disturbing that the maxima of the column density of HI (Fig.6) seem to be correlated with maxima of the terminal velocity, while the shock-wave theory predicts nearly the opposite behaviour (see Fig.1, where maxima of $\sigma$ correspond to minima of V).

The detailed profiles of HI at different longitudes can be well interpreted by density-wave models (e.g. Simonson 1976). Due to the many free parameters usually allowed in the models, the obtained agreement is, while certainly encouraging for density-wave theory, not finally decisive.

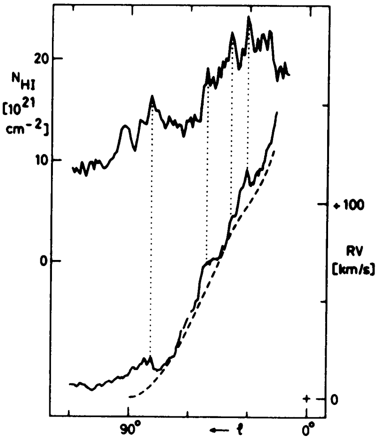


Figure 6. The lower part shows the terminal radial velocities of HI along the line of sight as a function of galactic longitude $\ell$ (data from Burton 1970). The upper part gives the integrated column density N(HI) as a function of longitude (data from Burton 1976).

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## 4.2. HII

In many external galaxies, giant HII regions are strongly confined to narrow spiral arms. If this is also true in our Galaxy, then the giant HII regions should be located on thin curves in the directly observable diagram of radial velocity RV versus galactic longitude $\ell$. Density-wave motions can only deform but not destroy the loops which correspond to the spiral arms in position space. Contrary to HI, velocity crowding would be unimportant for the HII features. The Figs.8, 9, 10 show the loops for a two-armed spiral structure in the cases of circular, pre-shock and post-shock velocities of HII regions. The observed diagram for HII regions (Fig.7) do not show the expected loops clearly. As long as it is rather impossible to deliniate the loops in the RV-$\ell$-diagram, there is no reason to expect a better definition of spiral arms in position space, no matter how accurate the velocity-distance relation may be. Fig.9 shows that the loops are more open and overlapping for the pre-shock case. Together with peculiar velocities of HII regions slightly higher than usually assumed, the pre-shock version may explain the blurring of the loops in the observed diagram for galactic HII regions. Star formation with pre-shock velocities is also favoured by observations of external galaxies (Wielen 1978).

The abundance of HII relative to HI as a function of galactocentric distance R can be explained by density-wave theory as due to a higher star formation rate in the inner part of the Galaxy, caused by the higher compression at the shock front and by the higher frequency of passages of the gas through the shocks. Both effects may also explain the high abundance of molecules ($H_2$, CO, etc.) in the inner region.

## 4.3. Studies of individual spiral arms

Although density-wave theory is mainly concerned with the grand design of spiral structure, this theory can also help one to understand the detailed structure and kinematics of nearby spiral arms on a smaller scale. Especially, non-circular motions and differences in radial velocities of HI, HII and young objects at the same location can be attributed to the density wave (e.g. Humphreys 1972, Roberts 1972, Minn and Greenberg 1973, Burton and Bania 1974). However, due to the complicated behaviour of young objects discussed in Section 2.3., it is difficult to make other than general qualitative statements of agreement.

## 4.4. Places of formation

Birthplaces of stars or clusters can be obtained by calculating their orbits backwards in time. The resulting pattern of birthplaces usually agrees well with the predictions of the density-wave theory (e.g. Yuan 1969, Wielen 1973, Grosbøl 1976). Unfortunately, the birthplaces of present nearby stars are strongly biased by a kinematic selection effect: Young objects ($\tau \leq 1\text{-}2 \cdot 10^8$ years) born in the main spiral arms, can have reached the Sun only if they had a rather large peculiar velocity at birth (see Figs.4 or 5). Furthermore, the diffusion of stellar orbits due

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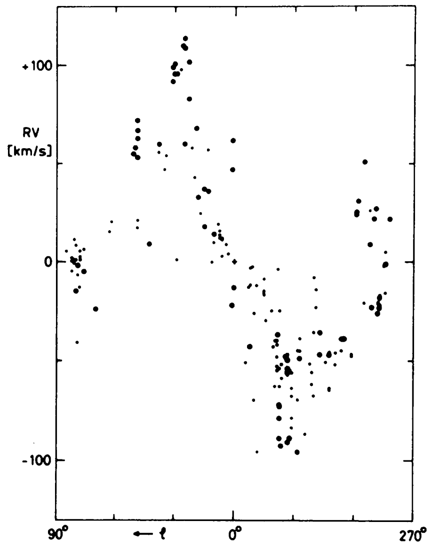


Figure 7. RV-ℓ-diagram for HII regions (giant regions: larger dots), based on H109α recombination line data of Reifenstein et al. (1970) and Wilson et al. (1970).

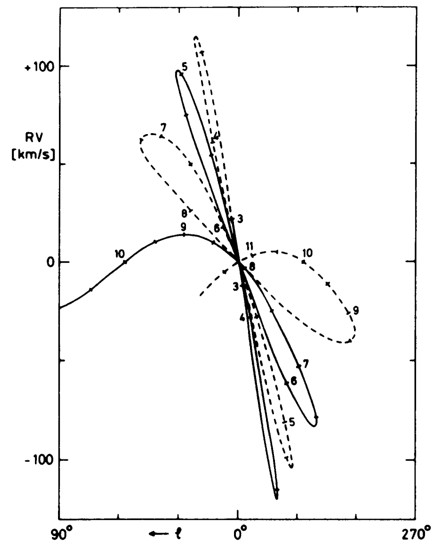


Figure 8. RV-ℓ-diagram for objects with circular velocities. The two spiral arms are distinguished by solid and dashed lines. The numbers indicate the distance from the galactic center.

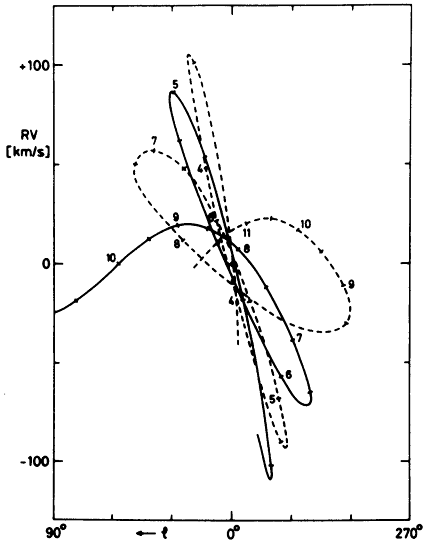


Figure 9. RV-ℓ-diagram of objects with pre-shock velocities at the shock front.

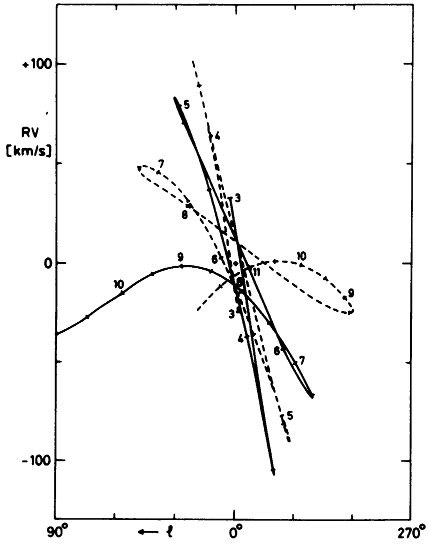


Figure 10. RV-ℓ-diagram of objects with post-shock velocities at the shock front.

to local irregularities of the galactic gravitational field probably causes severe uncertainties in the derived birthplaces of stars older than $10^8$ years (Wielen 1977).

4.5. Motions in the solar neighbourhood

Density-wave theory predicts significant non-circular motions for the gas and stars (Fig.3). These motions should be partially detectable in the solar neighbourhood, although local effects (e.g. the Orion arm) may severely disturb the global flow pattern. Lin et al. (1974) have studied the effect of shock waves in HI on the determination of the local galactic differential rotation. Probably the most easily detectable effect should be a positive K-term in HI: $K = 0.5 \text{ div } \vec{v} = -0.5\,\dot{\sigma}/\sigma$. Along a streamline, $\dot{\sigma}$ is mostly negative (Fig.1). K should be typically of the order of +6 km/s/kpc near the Sun. The available observations are however inconclusive.

In the presence of a density wave, the local mean velocity of objects of different age and different velocity dispersion should differ, and this can severely affect the determination of the local standard of rest (Blaauw 1970, Lin and Yuan 1975). If the Sun is located near the middle of an interarm region (e.g. at a spiral phase of 202°), the mean HI velocity, relative to the circular velocity, should be about $U = -\dot{R} = -10$ km/s and $V = +4$ km/s. While the predicted mean motion of young stars is rather uncertain (Section 2.3., Fig.3), the mean motion of old stars with a high velocity dispersion can be described by the linear theory. The amplitudes of the non-circular motions of older stars, $\hat{U}_*$ and $\hat{V}_*$, are correlated with the relative amplitude of their density variation, $(\hat{\sigma}_1/\sigma_0)_*$, by $\hat{U}_* = R(\Omega - \Omega_p) \tan i\, (\hat{\sigma}_1/\sigma_0)_*$ and $\hat{V}_* = R(\kappa^2/4\Omega) \tan i\, (\hat{\sigma}_1/\sigma_0)_*$. For $(\hat{\sigma}_1/\sigma_0)_* = 10\%$ and a pitch angle $i = 6\overset{\circ}{.}2$, we expect $\hat{U}_* = 1.2$ km/s and $\hat{V}_* = 1.1$ km/s (central oval in Fig.3).

In Fig.11, we present observational data on the mean velocities of various classes of objects with different velocity dispersions $\sigma_U$. Directly observable are not the absolute mean motions, but only the motions of the objects relative to the Sun, i.e. differences of mean velocities. Since young objects and gas probably deviate by about 10 km/s from circular motion, we must use older stars to define the local standard of rest, inspite of the larger mean errors. The most suitable objects seem to be the McCormick K + M dwarfs in Gliese's Catalogue of nearby stars (Wielen 1974c). The velocities of these dwarfs are not biased by selection effects. Since these K + M dwarfs are typical disk stars, their density amplitude $(\hat{\sigma}_1/\sigma_0)$ is probably less than 10%; hence their outward radial motion is about 1 km/s. The observed motion of the Sun relative to these K + M dwarfs, $U_\odot = +5\,(\pm 3)$ km/s, would then lead to a solar motion of $U_\odot \sim +4$ km/s relative to the local circular velocity. This value differs from the standard solar motion by about 6 km/s, and would explain perfectly the observed difference between the northern and southern galactic rotation curves (Kerr 1962) as due to an outward motion of the hitherto used local standard of rest. The V-component of the solar motion with respect to the circular velocity cannot be so easily derived, because

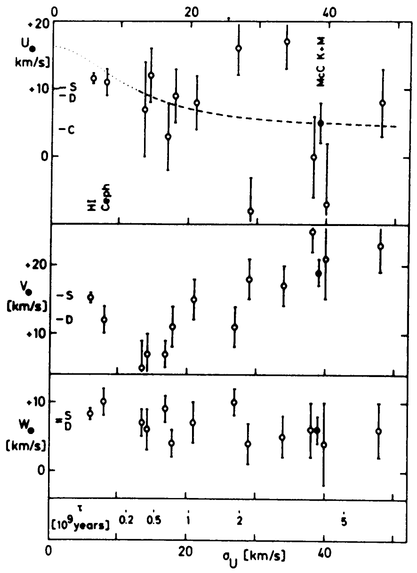


Figure 11. The solar motion for objects with various radial velocity dispersions $\sigma_U$ (and corresponding ages $\tau$). Data taken from Crovisier (1978), Jahreiß (1974), and Wielen (1974b, c). Mean errors are indicated. S = standard solar motion; D = peculiar solar motion after Delhaye (1965). A possible variation of $U_\odot$ with $\sigma_U$ according to the density-wave theory is schematically indicated by the dashed curve. C indicates the corresponding circular velocity. The dotted part of the curve is invalid because of the non-stationarity and/or the non-linearity of the motions of the objects with small $\sigma_U$.

the V velocities of the K + M dwarfs and of other old objects are affected by the classical 'asymmetric drift', which is difficult to eliminate quantitatively.

## 5. CONCLUSIONS FOR OUR GALAXY

Many observations in our Galaxy can be well explained by the presence of a density wave. This strongly suggests the actual existence of this wave, although most of the observations are not well suited as decisive tests at present. The observations have not provided a clue for the origin and maintenance of such a density wave. It is even unclear whether the observationally implied density wave in the gas is primarily caused by a tightly-wound spiral wave in the potential (mainly due to disk stars) or by a bar-like distortion of the inner parts of our Galaxy.

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DISCUSSION

Pişmiş: Dr. Wielen stated that the strongest argument supporting the density wave theory is the existence of the waves observed in the rotation curves of galaxies, the maximum velocity corresponding to the spiral arm and the minimum to the interarm region. The explanation for these waves is not unique. A possible, or even a more logical, explanation is afforded by the hydrodynamical equations of motion in a galaxy in steady state and with rotational symmetry. According to these equations, at a given distance from the galactic center the rotational velocity can have values from the circular velocity as a maximum down to values very small or even zero. It is easy to see that between the spiral arms the velocity of rotation must be low because we are observing there essentially an older population with a lower velocity of rotation with respect to the neighboring arms, where the rotation velocity is high.

Wielen: The wavy irregularities in the rotation curves have been observed mainly in HI, and partly in HII or young stars. All these objects have rather small velocity dispersions. Hence I do not think that the observed wavy irregularities can be explained in the way you propose.

Burton: Regarding the worry that the terminal velocity excursions are associated with local maxima in the HI apparent column densities: optical depth effects might be quite important. If typically $\tau \gtrsim 1$, an increase of some 5 km $s^{-1}$ of the total velocity extent will cause an increase of the integral $T_B(v)dv$ which might be sufficient to account for the observed increase in $N_{HI}$. It would be straightforward to test if this effect would dominate details in a model density distribution. It would be difficult, however, to correct the observations for these optical depth effects, because the true density distribution is too poorly known.

Wielen: Your data for the HI column density, which I used, were--at least partially--corrected for optical depth. If your explanation is correct, the optical depth effects have really to be extremely dominant for the HI profiles.

Bok: In the southern hemisphere we observe some spiral features (*e.g.*, the Carina arm) over a large range of distances. Can we predict average radial velocities for the young stars at the inside of the arm, in the middle, and at the outside of the arm? Would this allow us to differentiate between pre-shock and post-shock star formation? We also observe the Sagittarius arm cross-wise. Can we predict average velocity differences for stars between the Sun and the Sagittarius arm, those in the arm, and those lying slightly beyond the arm as viewed from the Sun?

Wielen: No detailed prediction of the kind you ask for has been made up to now, although this can be done in a quite straightforward way from our calculations. The velocities of the stars depend sensitively, how-

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ever, on the age, as shown in Figure 3 of my paper. A meaningful comparison between theory and observations can probably be carried out if the different ages of the observed objects are properly taken into account.

Meneguzzi: Do we see spiral features in old-population stars?

Wielen: We should not expect to see the linear density wave among the older disk stars in our Galaxy, because the amplitude of the density variation is probably of the order of 5 or 10%. The amplitudes of the non-circular motions may be about 1 km $s^{-1}$. According to Schweizer (1976), the density wave among older stars is visible in some external galaxies. The implied amplitudes, however, are sometimes disturbingly high. Perhaps there is still a significant contribution of younger stars to the observed smooth spiral arms.

Rickard: I got the impression from what you said that we should expect a rather poor agreement between the velocities of the young stars and the gas. But we know that there is good general agreement between the two--certainly not the large differences of $\sim$ 25 km $s^{-1}$ you discussed. I can recall only one case where the gas and stellar velocities in an HII region are as different as 12 km $s^{-1}$. In the Perseus arm there is a major HI feature well-correlated in velocity with the stellar velocities of the HII regions and young clusters. How do you explain this?

Wielen: The HII gas is probably co-moving with the young stars, on the average. So we would expect the two velocities to coincide except for some random velocity dispersion. The high-velocity differences between HI and young stars for the pre-shock case are maintained only for a short time (see Fig. 3 of my paper). Because the young stars remain for a rather long time in the neighborhood of the spiral shock front, the average difference in velocity between HI and young stars may be small. In the Perseus arm, the shock strength is probably small, because the gas motion is only slightly supersonic ($W_{\perp} \sim a$). Therefore, the difference between the pre- and post-shock velocities should be smaller than those shown in Figure 3, which illustrates the situation at R $\sim$ 10 kpc.