APPLICATION OF THE DENSITY-WAVE THEORY OF SPIRAL STRUCTURE: SHOCK FORMATION ALONG THE PERSEUS ARM

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ABSTRACT

An examination of (1) recent optical data on O associations, young open clusters, H II regions, and interstellar absorption lines and (2) recent high-resolution 21-cm hydrogen maps of the Perseus spiral arm indicates that the systematic motion of order up to 20 km s\(^{-1}\) associated with the interstellar medium may be a significantly more extended phenomenon than previously recognized, stretching from a longitude of \(l = 100^\circ\) all the way around to \(l = 200^\circ\) and perhaps beyond. In light of the observational data, a model based on the density-wave and galactic-shock-wave concepts is proposed for the Perseus arm. The model considered is the two-armed spiral shock (TASS) model that delineates the large-scale spiral structure and describes the large-scale motion of the interstellar gas, and the young optical objects born out of the gas, over the galactic disk. In this model, the Perseus arm is visualized to consist of a galactic shock wave embedded in a background density wave. The systematic motion observed along the entire length of the Perseus arm can be accounted for as the systematic motion predicted in the TASS model. Splitting of an H I feature into multiple subcomponents of the type found in observed profiles of neutral hydrogen arises rather naturally in the presence of a galactic shock. When the observational data are interpreted through the TASS model, the apparent discrepancy between the position of the optical spiral arm and that of the neutral-hydrogen spiral arm is found to disappear, and the overall Perseus feature becomes one composite arm. Secondary arms are found to be possible in the outer parts of the TASS model, and these bear some resemblance to the secondary arms, “spurs,” and “feathers” which are often observed in the outer parts of external spiral galaxies and our own Milky Way system.

I. INTRODUCTION

O associations, young open clusters, and H II regions have come to be known as the optical tracers of spiral structure in our own Galaxy, as well as external spiral galaxies. Even from the early optical studies on (1) distances to O associations by Morgan, Whitford, and Code (1953), (2) radial velocities of members of associations by Wilson (1953), (3) space distribution of open clusters by Becker (1963) and by Hoag and Applequist (1965), and (4) space distribution of H II regions by Sharpless (1959, 1965), spiral arms in our Galaxy were recognizable. Now, a considerably refined and reasonably clear-cut optical picture of the spiral structure surrounding the solar neighborhood has emerged from the recent optical work on (1) space distribution of H II regions by Murdin and Sharpless (1968) and open clusters according to age by Becker and Fenkart (1970a) and (2) radial velocities of H II regions by Courtes, Cruvellier, and Georgelin (1968) and Georgelin and Georgelin (1970) using Fabry-Perot techniques and by Miller (1968) using spectrographic methods. To be sure, the radio studies of neutral hydrogen have played their important part as well. On the larger scale of the overall galactic disk, the panoramic picture of the large-scale spiral structure has sprung from the studies of the distribution of neutral hydrogen through 21-cm line emission by van de Hulst, Muller, and Oort (1954), Kerr and Westerhout (1965), Westerhout (1966, 1969), Kerr (1970), and Weaver (1970).

Included in all of these studies, the Perseus arm has to be one of the most extensively studied features of our Milky Way system. Yet the Perseus arm is still a rather intriguing

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puzzle. Even in the most recent map of the spiral structure of our Galaxy (see Bok 1970), the optical and radio spiral features in the Perseus-arm region—contrary to what would be expected—do not coincide. While the optical arm lies relatively close to the solar neighborhood at a distance of about 2–3 kpc, the $\text{H} \alpha$ arm, whose position is derived through a dependence on the 1965 Schmidt model, is drawn much farther away at a distance of about 3–5 kpc and is much less inclined and more closely circular.

Münch (1957) measured the radial velocities and intensities of Ca $\pi$ and Na $\pi$ interstellar absorption lines seen in front of large O associations in the Perseus arm. At that time Münch noted a great deal of multiplicity in line components, some of which had considerably higher negative velocities than the associations themselves and thus according to the Schmidt model should refer to material behind those associations. He concluded that part of the interstellar gas observed in front of these O associations is departing from circular motion and is approaching along the line of sight with speeds up to $20 \text{ km s}^{-1}$. Rickard (1968) examined the optical and radio evidence for the large-scale systematic motions over the portion of the Perseus arm between $l = 97^\circ$ and $l = 150^\circ$. He showed that the optical interstellar absorption lines found by Münch are well correlated with major concentrations of neutral gas. In her study of the distribution and kinematics of supergiants in the Perseus arm, Humphreys (1970) showed that the supergiants as well participate in this systematic noncircular motion. She found that those associations with supergiant members lying on the inner side of the Perseus arm generally seem to have a larger systematic component of motion toward the Sun than those on the outer side, by typically $10 \text{ km s}^{-1}$. Furthermore, she showed that this systematic motion of the supergiants seems to indicate a shearing motion along the entire length of the arm. The recent work of Courtes et al. (1968) and Georgelin and Georgelin (1970) further suggests that the systematic motion may extend over an even larger region of the sky than heretofore recognized, stretching from $l = 100^\circ$ up to $l = 200^\circ$ and perhaps beyond.

It is important to recognize that no adjustment of the smooth equilibrium rotation curve can account for this systematic motion, and in particular for the optical absorption line data relative to the background objects. In light of this and other evidence, a model for the Perseus arm based on the density-wave and galactic-shock-wave concepts (Lin and Shu 1964, 1966; Lin, Yuan, and Shu 1969; Roberts 1969; Roberts and Yuan 1970) is considered in this paper. In the framework of the two-armed spiral shock (TASS) model (see Roberts 1969), the large-scale motion of the interstellar gas$^1$ is investigated with particular emphasis on the region of the galactic disk between the radii of 10 and 13 kpc, across which the Perseus arm stretches. In this model, the Perseus arm is visualized to consist of a galactic shock wave embedded in a background density wave. It is found that the systematic motion of the interstellar gas, and the young objects born out of the gas, in the Perseus-arm region can be accounted for as the systematic motion predicted in the TASS model. Various other pieces of the observational data that together make up the puzzle of the Perseus arm can be accounted for. Splitting of an H $\alpha$ feature into multiple subcomponents of the type found in observed profiles of neutral hydrogen is shown to be a natural consequence of the galactic shock. In practice, the equilibrium Schmidt model has generally been the model used for the determination of the distance of an H $\alpha$ arm. It is found that this conversion from line-of-sight velocity to distance for the gaseous feature in the Perseus-arm region is somewhat misleading when the equilibrium model is used. When conversion from velocity to distance is made through the TASS model, the present discrepancy between the position of the H $\alpha$ and the positions of the stars in the Perseus arm is found to disappear, and the two arms—optical and radio—are found actually to coincide as one composite arm.

$^1$Since the young optical objects have only very recently been born out of the interstellar gas, the large-scale motion of the young optical objects may very closely resemble the large-scale motion of the interstellar gas.
II. DYNAMICS IN THE OUTER PARTS OF THE GALACTIC DISK

The equilibrium model we adopt for our own Galaxy is the 1965 Schmidt model (Schmidt 1965). We are primarily concerned with the region of the galactic disk just exterior to the solar neighborhood where, in contrast to the inner regions of the Galaxy, an observational determination of the smooth law of rotation is not possible. We should therefore keep in mind that the Schmidt law of rotation is an extrapolation over this region. Suppose we now superpose on this equilibrium disk a two-armed spiral pattern of density waves (Lin and Shu 1964, 1966; Lin et al. 1969). Viewing this composite model through the density-wave theory, we have a single mode, or a group of modes, making up the density-wave pattern which is assumed to rotate about the galactic center at a constant angular speed. The interstellar gas as well as all other matter moves about the disk through the wave pattern and responds spontaneously to the underlying gravitational field. Since there are really two separate components of the disk, gaseous and stellar, we shall assume that the background density wave can be attributed mostly to the more massive stellar component in the disk, and we shall be primarily concerned with the response of the gaseous component to the gravitational field of the background density wave.2

We consider the motion of an isothermal gas with a mean equivalent turbulent-dispersion speed. The emphasis here is directed toward the two dimensional motion of the gas. The overall picture may be considered from a rather natural point of view. To an observer, fixed in the coordinate system rotating at the pattern speed about the galactic center, the wave pattern is stationary, and the gas flow is steady. In the framework of this picture, which was the picture adopted in Roberts (1969) without magnetic fields and in Roberts and Yuan (1970) with magnetic fields, we determine here the detailed nature of the gas flow on the scale of an individual arm.3 The methods of approximation and solution of the hydrodynamic equations governing the dynamics of the gaseous disk are identical with those described in Roberts (1969); and equations (18), (19), (21), and (22) there make up the system of equations that are solved numerically here.

The nonlinear response of the gas is found to be one in which shock waves form and are maintained along the background density-wave arms. This large-scale response delineates a two-armed spiral shock (TASS) pattern. For particular application to the region of the TASS picture just outside the solar circle where the Perseus arm lies, the independent parameters that govern the nature of the gas flow take on values which lie in the following typical ranges: \( \omega \), average radius of a gas streamtube, 10–13 kpc; \( i \), pitch angle of the TASS pattern, 6°–15°; \( \Omega_p \), pattern speed, 12–13 \( \text{km s}^{-1} \text{kpc}^{-1} \); \( F \), amplitude of the spiral gravitational field taken as a fixed fraction of the smoothed axisymmetric field, 5–7.5 percent; \( a \), mean equivalent dispersion speed of the gas, 6–10 \( \text{km s}^{-1} \). These narrow ranges, determined partly from observational studies, are similar to those adopted in Roberts (1969) and together define a rather small subspace in five-dimensional parameter space. At any point throughout this subspace where each parameter takes on its assigned value, the general nature of the gas-flow solution is qualitatively the same. Once these parameters are specified, the location of the shock with respect to the background spiral gravitational field is uniquely determined. A variety of cases are considered in which the four parameters \( i \), \( \Omega_p \), \( F \), and \( a \) take on different values throughout this subspace. In each case, a fourfold procedure of comparison of the model with observations in the region of the galactic disk outside the solar circle is undertaken, based on (1) space distribution of the young optical objects, (2) line-of-sight velocities of these

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2 The gaseous response gives rise to a gravitational field which enhances the originally imposed perturbing gravitational field of the background density wave. With this enhancement, the imposed field may be regarded as the resultant field of the gas, young stars, and moderately old stars.

3 For simplicity here we assume that the magnetic field is weak and that the hydromagnetic forces do not play an important role. In § VI the effect of the magnetic field will be discussed.
young objects, (3) interstellar-absorption-line data, and (4) brightness-temperature profiles derived from 21-cm line contour maps of neutral hydrogen. Two such cases which can account for the observational data are presented in this paper. Presented in § IV is the TASS model of 12° pitch angle ($\Omega_p = 12.5 \text{ km s}^{-1} \text{kpc}^{-1}, F = 7.5$ percent, $a = 8 \text{ km s}^{-1}$). In § V the TASS model of 8° pitch angle ($\Omega_p = 12.5 \text{ km s}^{-1} \text{kpc}^{-1}, F = 5$ percent, $a = 8 \text{ km s}^{-1}$) is presented.

Numerical calculations show that the basic features of the TASS model for the region of the disk outside the solar circle (see fig. 1) are similar to those basic features for the region inside the solar circle (see figs. 3–7 of Roberts 1969). In both regions, the shock occurs within the potential well of the background density wave. Some physical justification for the location of the shock can be seen if we examine the actual potential field that the gas sees in its motion along a streamtube (see fig. 1). Because the front side of this potential well is so steep, gas rushes down into the potential well rather rapidly, creating a tendency for the “piling up” of gas near the bottom. The shock can be envisaged as simply the manifestation of this piling up of gas. After being compressed in the shock, the gas leaves the potential well rather slowly at subsonic speeds. In the regions both inside and outside the solar circle the shock, the sharp H I peak, and the

Fig. 1.—Gas density distribution, $\sigma' = (\sigma_0 + \sigma_1)/\sigma_0$, along a typical streamtube in the TASS model outside the solar circle: $\sigma_0$, mean density; $\sigma_1$, perturbed density. The TASS (two-armed spiral shock) model shows a tendency for multiple spiral features (>2) in its outer parts. Here in the region outside the solar circle a secondary gas peak with a possible secondary shock occurs in addition to the primary shock and the prominent gas peak.
prominent dust lane all outline a rather narrow strip along the inner edge of the observable gaseous spiral arm which itself consists of O associations, young open clusters, and H II regions triggered by the shock as well as H I and dust. Roberts and Yuan (1970) considered a possible model for the galactic magnetic field and found that a moderately strong magnetic field of about 5 microgauss may also permeate this narrow shock strip where the H I and dust are most prominent, both inside and outside the solar circle.

On the other hand, the numerical calculations show that one fundamental difference is present between the two regions of the model inside and outside the solar circle. Inside, the gaseous response is determined to be one in which two prominent arms of gas form. Outside the solar circle, secondary arms of gas are also found to arise along with the two prominent arms of gas already present which delineate the TASS pattern. In this outer region of the model, there is the further tendency for the formation of a secondary shock (see fig. 1, dashed curve) out of the secondary arm. In this situation, a further triggering of star formation is possible along the secondary H I arm. The numerical calculations therefore show that a two-armed response is possible in the inner region, but a multiple-armed response with more than two arms is more likely in the outer region. To be sure, the multiple arms, "spurs," and "feathers" that are often observed in the outer parts of external galaxies and our own Milky Way system might well be combinations of primary and secondary arms of the type found in this model.

A simplified interpretation for this computed result of a multiple-armed response in the outer region is possible if we examine the parameter

\[ \nu(\alpha) = \frac{2(\Omega_p - \Omega(\alpha))}{\kappa(\alpha)}, \]

which plays an important role in the linear density wave-theory of Lin and Shu (1964, 1966). The quantity |\nu| measures the frequency at which a material particle passes through the density-wave pattern relative to the frequency at which the particle oscillates about its epicyclic orbit. In the region of the disk between the radii of 3 and 10 kpc, |\nu| is typically close to 1.0. In this region an individual star or gas particle would find it rather natural to undergo about one epicyclic oscillation for every half-revolution of its orbit about the pattern. Each time the particle passes through a spiral arm, it would be roughly at the same phase of its epicyclic orbit. For a collective system of self-gravitating gas and stars participating in phase, the outer portion of the collective orbit where the particles travel most slowly about the disk is the region where the system of particles is densest and where a density-wave arm could be manifested. With two epicyclic oscillations of the collective system per revolution about the pattern, two density-wave arms could be maintained. On the other hand, in the region between 10 and 13 kpc just outside the solar circle, |\nu| is typically much smaller (e.g., 0.5); and for even larger radii, |\nu| decreases even further toward the value of zero at corotation. In this outer region an individual star or gas particle feels the tendency to undergo more than one epicyclic oscillation for each half-revolution of its orbit through the pattern. More than two density-wave arms could therefore be expected to be manifested by the collective system in the outer region.

III. THE OBSERVATIONAL DATA FOR THE PERSEUS-ARM REGION

In tables 1, 2, and 3 are tabulated the optical data lying in the longitude range 90° < l < 200°; in the latitude range -4° < b < +4°; and with a distance from the Sun, d, greater than about 1.25 kpc.

a) O Associations

The O associations found in the Perseus-arm region are listed in table 1. Their galactic coordinates (cols. [2] and [3]) and distances (col. [4]) are taken from the published
### TABLE 1
O Associations

<table>
<thead>
<tr>
<th>Association</th>
<th>$l$</th>
<th>$b$</th>
<th>$d$</th>
<th>$(v_L)_L$</th>
<th>Source</th>
<th>$v_L$</th>
<th>ISL*</th>
<th>Source</th>
</tr>
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<tr>
<td>Cep OB1</td>
<td>103.0</td>
<td>-1.8</td>
<td>3.60</td>
<td>-46.6</td>
<td>H</td>
<td>-46,(-44),(-34),(-31),(-27,(-24)</td>
<td>Mch</td>
<td></td>
</tr>
<tr>
<td>Cep OB5</td>
<td>108.5</td>
<td>-2.8</td>
<td>2.09</td>
<td>-47.9</td>
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<td>...</td>
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<td>Cas OB2</td>
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<td>-1.9</td>
<td>2.45</td>
<td>-37.7</td>
<td>H</td>
<td>-52,(-50),-38</td>
<td>Mch</td>
<td></td>
</tr>
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<td>Cas OB4</td>
<td>120.3</td>
<td>0.0</td>
<td>2.65</td>
<td>-38.6</td>
<td>H</td>
<td>(-59), (-34)</td>
<td>Mch</td>
<td></td>
</tr>
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<td>Cas OB7</td>
<td>123.5</td>
<td>+0.9</td>
<td>2.34</td>
<td>-36.9</td>
<td>H</td>
<td>-57,(-52),(-38),(-33)</td>
<td>Mch</td>
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<tr>
<td>Cas OB1</td>
<td>124.0</td>
<td>-1.4</td>
<td>2.63</td>
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<td>-60,(-39),-37</td>
<td>Mch</td>
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<td>-0.8</td>
<td>2.94</td>
<td>-43.1</td>
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<td>...</td>
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<td>Per OB1</td>
<td>134.8</td>
<td>-3.7</td>
<td>2.30</td>
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<td>-57, (-50, -43, -39)</td>
<td>Mch</td>
<td></td>
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<td>...</td>
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<td>3.50</td>
<td>-34.9</td>
<td>H</td>
<td>(-45)</td>
<td>Mch</td>
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<td>Aur OB1</td>
<td>173.1</td>
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<td>1.34</td>
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<td>-19,-15,-4</td>
<td>Mch</td>
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<td>Mch</td>
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<td>-7,6, (1)</td>
<td>Mch</td>
<td></td>
</tr>
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</table>

**Note.**—Distances and galactic coordinates are taken from the Transactions of the I.A.U. (1964).

* The $V$-component of interstellar absorption, as determined by Münch, is enclosed in parentheses if it is not resolvable into $V_1$ and $V_2$ subcomponents. The $V_1$ and $V_2$ subcomponents, when resolvable, appear without parentheses.

### TABLE 2
Young Open Clusters

<table>
<thead>
<tr>
<th>Cluster</th>
<th>$l$</th>
<th>$b$</th>
<th>$d$</th>
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<th>Source</th>
<th>$v_L$</th>
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<td>97.4</td>
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<td>+0.8</td>
<td>4.08</td>
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<tr>
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<td>NGC 7380</td>
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<td>2.82</td>
<td>-27.0</td>
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<td>NGC 7510</td>
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<td>2.88</td>
<td>-57.0</td>
<td>J&amp;S</td>
<td></td>
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<tr>
<td>Ba 3</td>
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<td>2.21</td>
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<td>K14</td>
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<td>2.10</td>
<td>-33.0</td>
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<td>1.87</td>
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**Note.**—Distances are taken from Becker and Fenkart (1970b).
DENSITY-WAVE THEORY

TABLE 3

H ii Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>l</th>
<th>b</th>
<th>d</th>
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<th>(vLS) LSR</th>
<th>Source vLS</th>
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values in the Transactions of the International Astronomical Union (1964). The line-of-sight velocities with respect to the local standard of rest (col. [5]) are taken from Humphreys (1970, 1971). Also included in column (7) are the line-of-sight velocities with respect to the local standard of rest of the interstellar absorption lines seen in front of O associations taken from Münch (1957, 1965).

b) Young Open Clusters

Becker (1963) studied the space distribution of some 150 open clusters according to spectral type. He found that the clusters of earliest type between O and B2 trace out three spiral features surrounding the vicinity of the Sun: the Perseus, “Orion,” and Sagittarius arms; while the later-type clusters show a more or less random distribution in space. More recently Becker and Fenkart (1970a) carried out a new survey containing some 250 clusters in which the determination of distance is based on a method using both the $B - V$ and $U - B$ color-magnitude diagrams but not the two-color diagram. From these studies it appears that roughly 70 percent of the clusters in the Perseus arm are of O–B2 type, while O–B2 clusters in the “Orion arm” make up less than 30 percent of the total number there. By comparison, this suggests the Perseus arm is a very young arm, and perhaps capable of maintaining its youth, while the “Orion arm” is not. Listed in table 2 are the O–B2 clusters, their galactic coordinates, and distances taken from Becker and Fenkart (1970b). In columns (5) and (6) are the line-of-sight velocities with respect to the local standard of rest, and sources where these velocities are published: J&S = Johnson and Svolopoulos (1961), W = Wilson (1953).

c) H ii Regions

In table 3 are listed the H ii regions in the Perseus arm, their galactic coordinates, distances, sources of distance, line-of-sight velocities with respect to the local standard
of rest, and sources of velocity. Distances to H\textsc{ii} regions and line-of-sight velocities are taken from the following sources: C = Courtes \textit{et al.} (1968), D = Dieter (1967), G&G = Georgelin and Georgelin (1970), M = Miller (1968), M&S = Murdin and Sharpless (1968), and Mz&H = Mezger and Höglund (1967). When the distance to an H\textsc{ii} region or its line-of-sight velocity is estimated by more than one of the sources, an average value for the distance or velocity is derived, and all sources involved in the average are listed.

\textbf{d) Distribution of Neutral Hydrogen}

The 21-cm line contour maps of antenna temperature in the Maryland-Greenbank 21-cm line survey of Westerhout (1966, 1969) have been taken and used to derive antenna-temperature profiles for the H\textsc{i} distribution averaged over galactic latitude in the range from $b = -1.0^\circ$ to $b = +1.0^\circ$.

\textbf{IV. A DENSITY-WAVE–SHOCK-WAVE MODEL}

As one of the major spiral features making up the large-scale grand design of spiral structure in our Galaxy, the Perseus arm is visualized to consist of a galactic shock wave embedded in a background density wave of the TASS model. Here the TASS model with $12^\circ$ pitch angle ($\Omega_p = 12.5 \text{ km s}^{-1} \text{ kpc}^{-1}$, $F = 7.5$ percent, $a = 8 \text{ km s}^{-1}$) is presented.

\textbf{a) Location of the Shock: Space Distribution of the Young Optical Objects}

In figure 2 is sketched the space distribution of the O associations, O–B2 clusters, and H\textsc{ii} regions listed in tables 1, 2, and 3. All available data which could be associated with the Perseus arm in the longitude range from $l = 90^\circ$ to $l = 200^\circ$ is sketched. Gas flows in the clockwise sense about the galactic center and passes from left to right through the shock-wave pattern which is rotating at the slower pattern speed. In the presence of a prominent galactic shock that may be capable of acting as a large-scale triggering mechanism, the newly born, luminous optical objects found in the Perseus-arm region, after being triggered into existence in passage through the shock, lie within or behind the shock. Those few that are apparently located in front of the shock may have been triggered into existence by some means capable of initiating star formation other than the shock. On the other hand, the uncertainty in the measurement of distances to these young objects is on the order of 400 pc and no doubt contributes to the large spatial scatter along the line of sight; this could very well be the real reason why a few of the objects appear to lie in front of the shock.

\textbf{b) Results for a Typical Longitude Range: $l = 130^\circ–140^\circ$}

\textbf{i) Line-of-sight velocities of the gas and young optical objects}

In the shock model the theoretical line-of-sight velocity, $v_{LS}$, of the interstellar gas and the young objects born out of the gas can be determined at any point in the galactic disk as a function of longitude and distance from the Sun. In the lower left portion of figure 3 a plot of line-of-sight velocity versus distance is sketched for the longitude interval $l = 130^\circ–140^\circ$. In this direction the basic motion of the gas is from left to right. The smooth solid curve with crosses represents the line-of-sight velocity for objects obeying the equilibrium Schmidt model (Sch.) for purely circular motion about the galactic disk. Superposed on this plot are the O associations (○), O–B2 open clusters (△), and H\textsc{ii} regions (■), found in this longitude range. It is interesting to note that all the objects, except for one, lie below the Schmidt model curve. As a group, these objects would appear to have a net negative systematic component of motion toward the Sun of the order of $10 \text{ km s}^{-1}$. The dashed curve corresponds to the line-of-sight velocity predicted in the linear density-wave model (L.D.W.). The heavy solid curve represents the line-of-sight velocity predicted in the TASS model. At the shock some of the largest gas clouds may be compressed beyond their verge of gravitational collapse, and thereby the
Fig. 2.—Location of the shock and space distribution of the young optical objects in the Perseus arm. Gas flows in the clockwise sense about the galactic center and passes from left to right through the shock. The shock is visualized as a large-scale triggering mechanism for gas-cloud collapse, leading to star formation. As the young optical objects form, they continue to move with the gas through the shock from left to right and beyond. Spottiness of the luminous, newly born objects, which we now observe, is expected because of distance uncertainty of the objects; because of perturbations in density and temperature in the gas which influence irregularity along the shock, nonuniformity in the shock compression, and varying evolution periods among the triggered objects; and because of the random scattering throughout the shock region of the most prominent perturbations from which these objects could be triggered.

The birth of young optical objects is triggered. Passing through and beyond the shock, these large clouds evolve into the very luminous optical objects that are now seen in a time period of perhaps 5 to 50 million years from the initial stages of their compression in the shock. Because of their velocity dispersion of the order of 8 km s\(^{-1}\) or even higher, it is not unreasonable to expect these objects to exhibit the velocity scatter they do. The two dotted curves outline a dispersion band where the gas with a mean velocity dispersion of 8 km s\(^{-1}\) would lie in the TASS model. Distance uncertainty no doubt also contributes to the apparent spatial scatter about the TASS curve. In view of these two factors that contribute to the scatter, nine of the ten young optical objects lie within the region predicted by the TASS model.

ii) Gas-density distribution

In the upper left portion of figure 3 is a plot of the gas-density distribution predicted in this longitude range in the TASS model. While the peak of H\(\alpha\) and dust lies just be-
Fig. 3.—Theoretical features of the 12° TASS model in the longitude range l = 130°–140°. Lower left, line-of-sight velocity versus distance from the Sun. The basic motion of the gas is from left to right. Sch (solid curve with crosses), equilibrium Schmidt model. L.D.W. (———), linear density-wave model. Heavy solid curve (-----), TASS model. The two dotted curves (.....) outline a dispersion band of ±8 km s\(^{-1}\) about the TASS curve. O, O associations; △, O-B2 open clusters; ■, H\(\text{II}\) regions. Having evolved into their luminous stages of evolution some 5–50 million years after the initial stages of their triggering at the shock (Region B), these young luminous objects have migrated with the gas to Region C, several hundred parsecs beyond the shock. The interstellar absorption-line data of Münch (ISL) provide the strongest observational evidence for systematic motion along the Perseus arm. Here the galactic shock appears as a rather essential feature in order to account for these lines, particularly those at large negative velocities (e.g., \(V_2\)). Upper left, gas density distribution, \(\sigma' = (\sigma_0 + \sigma_1)/\sigma_0\), versus distance from the Sun. Lower right, upper right, theoretical number-density and brightness-temperature profiles, respectively. The profiles for mean turbulent dispersion speed \(c = 3\) km s\(^{-1}\) and \(c = 8\) km s\(^{-1}\) are plotted along with the observed brightness-temperature profile (solid curve with crosses) derived from Westerhout (1966, 1969). Splitting of the overall H\(\text{I}\) feature in the profile into multiple subcomponents and peaks is a rather natural tendency in the presence of a shock. In the profile for \(c = 3\) km s\(^{-1}\), the contribution to peak E comes almost entirely from the effect of "velocity crowding" which occurs in Region C where a substantial amount of rarefied gas is located along a large distance over the velocity hill. Here the effect of the galactic velocity field on the profile is so important that it cannot be underemphasized. On the other hand, the contribution to peak F comes from both Region B, the dense gas just behind the shock, and Region D, the less dense gas in the secondary peak.
hind the shock, the young optical objects all lie a little beyond. Although not terribly striking here, the secondary peak of gas corresponds to a substantial trough in velocity.

iii) Interstellar absorption-line data

In the direction of the O association Per OB1 in this longitude range, Münch (1957) found that the V-line of interstellar absorption is actually multiple with mean subcomponents $V_1$ and $V_2$. He measured the mean velocity of the $V_1$ component at about $-39$ km s$^{-1}$ and that of the $V_2$ component at about $-57$ km s$^{-1}$. In the lower left portion of figure 3 these mean subcomponents, together with other observed subcomponents at $-43$ and $-50$ km s$^{-1}$, are sketched adjacent to the shock (I.S.L.). According to the TASS model the $V_1$ subcomponent corresponds to clouds that lie several hundred parsecs behind the shock in the vicinity of the O associations, while the $V_2$ subcomponent corresponds to clouds embedded in the dense matter just behind the shock where the H I peak occurs. Indeed, the shock appears to be necessary in order to account for the high negative $V_2$ subcomponent of interstellar absorption. Here, the mean $V_2$ subcomponent and the line at $-50$ km s$^{-1}$ can easily be accounted for if they are associated with clouds that lie in the region just behind the shock. If no shock were present, such as in the equilibrium Schmidt model, the $V_2$ subcomponents could be associated only with clouds that are far more distant than the O associations themselves. Even the linear density-wave model (L.D.W.) cannot account for the $V_2$ subcomponent, for here again the only possible clouds with which to associate these absorption lines are far more distant than the O associations themselves.

iv) Number-density and brightness-temperature profiles

Before number-density and brightness-temperature profiles can be determined from the model, it is first necessary to decide upon mean values for three quantities: (a) the mean speed $c$ for turbulent motions of the gas clouds in the interstellar medium; (b) the mean number density of neutral hydrogen, $n_H$; (c) the mean spin temperature $T_s$ for the interstellar medium. The first of these three quantities, $c$, contributes to the mean equivalent turbulent-dispersion speed, $a$, of the gas. In turbulent gas with cosmic rays present, the square of the mean equivalent turbulent-dispersion speed $a$ may be interpreted as the sum of the mean square values of the effective turbulent-dispersion speed, partly kinetic and partly due to turbulence, and the effective speed of the gas contributed from the cosmic ray pressure. The speed $a$ of turbulent motions is typically 3-8 km s$^{-1}$.

The second quantity to be chosen is $n_H$. Once a mean value for $n_H$ is adopted, a number-density profile which shows the amount of gas $n_H(v_{LS})$ that moves at a specified line-of-sight velocity $v_{LS}$ within a unit velocity interval can be calculated according to the following formula:

$$n_H(v_{LS}) = \frac{3 \times 10^{20} n_H^0}{(2\pi)^{1/2} c} \int_0^\infty \sigma'(r, l) \exp \left\{-[v_{LS} - v_{LS}(r, l)]^2/(2\sigma^2)\right\} dr ,$$

(2)

where $\sigma'(r, l)$ is the contrast in gas density along the line of sight plotted in the upper left portion of figure 3. The mean number density $n_H^0$ is taken as a constant, 0.2 H cm$^{-3}$ throughout; this fixes the height of the theoretical profile. In the lower right portion of figure 3, two theoretical profiles (solid curves) for turbulent speeds of $c = 3$ km s$^{-1}$ and $c = 8$ km s$^{-1}$ are sketched for the longitude range $l = 130^\circ-140^\circ$. The number-density profile for $c = 8$ km s$^{-1}$ is broader; the profile for $c = 3$ km s$^{-1}$ is narrower and more

4 The acceleration of gas by O stars in expanding O associations could contribute toward shifting the interstellar absorption lines toward more negative velocities than they would ordinarily have. However, it is difficult to believe that the large observed shifts of 10-20 km s$^{-1}$ could be attributed to this type of expansion alone. It is also difficult to explain the existence of these subcomponents of large negative velocity along the entire length of the Perseus arm by this local expansion.
sharply peaked. Superimposed is the observed antenna-temperature profile (solid curve
with crosses) which is determined by averaging, over a $-1^\circ$ to $+1^\circ$ latitude range, the
antenna temperatures in the contour maps of neutral hydrogen in the Maryland-Green-
bank 21-cm line survey (see Westerhout 1966, 1969).

Once a mean spin temperature $T_\alpha$ is adopted, a brightness temperature $T_b$ is derived
by the following relation:

$$T_b = T_\alpha(1 - e^{-\tau}),$$

(3)

where the optical depth $\tau$ is given by

$$\tau = \frac{n_H}{1.823 \times 10^{18} T_\alpha}.$$  

(4)

It is important to recognize that for any choice of the mean value of $T_\alpha$ above a few
hundred degrees K, the gas is optically thin, $\tau \ll 1$, and the brightness temperature $T_b$
is essentially independent of $T_\alpha$. For example, whether $T_\alpha$ is $300^\circ$ K or $10^4^\circ$ K, the bright-
ness temperature is essentially the same:

$$T_b \approx T_\alpha \tau \approx \frac{n_H}{1.823 \times 10^{18}}.$$  

(5)

Therefore, the choice of the mean value of $T_\alpha$ is not so critical. The theoretical bright-
ess-temperature profiles plotted in this paper are based on a mean value of $10^3^\circ$ K for
$T_\alpha$. In the upper right portion of figure 3 two theoretical brightness-temperature profiles
for $c = 3$ km s$^{-1}$ and $c = 8$ km s$^{-1}$ are compared with the observed antenna-tempera-
ture profile (solid curve with crosses) determined from Westerhout (1966, 1969). It is be-
cause the gas is optically thin that these theoretical brightness-temperature profiles are
only slightly truncated from the number-density profiles sketched in the lower right
portion of figure 3.

The theoretical number density and brightness temperature profiles for $c = 3$ km s$^{-1}$
best isolate the regions that are associated with and contribute most strongly to the fea-
tures in the profiles. The prominent peak E located at $-40$ km s$^{-1}$ may be attributed to
the substantial amount of rarefied gas integrated along the large distance over the veloc-
ity hill C in the lower left portion of figure 3. Although quite prominent, the contribu-
tion to peak E comes almost entirely from “velocity crowding” rather than from a spa-
tially dense region of gas. Because the velocity gradient just behind the shock is so large
and therefore because only a small proportion of the dense gas in the narrow lane B just
behind the shock lies within each unit velocity interval, Region B contributes in only a
moderate proportion to this first peak E. The second prominent peak F at about $-58$
km s$^{-1}$ can be attributed partly to the very dense gas in the narrow lane B just behind
the shock and partly to the region of less dense gas comprising the secondary peak D.
Because the velocity gradient just behind the shock (Region B) is so large and because
the velocity gradient in the secondary peak D is rather gradual, these two sources B
and D, which occur at roughly the same velocity, contribute about equally to the sec-
ond peak F at $-58$ km s$^{-1}$. Hence, two major peaks E and F in the profile are distin-
guishable in this longitude range. Over some longitude ranges the shock (with Region
B), velocity hill C, and secondary peak D, which are the primary contributors to the
profile, have so nearly the same line-of-sight velocity that only one peak is distinguish-
able. A maximum of three peaks is possible when the shock (with Region B), velocity
hill C, and secondary peak D occur at substantially different line-of-sight velocities.
Indeed, a multiplicity of subcomponents and peaks in the profile seems to be a rather
natural consequence of the shock model.\(^5\)

\(^5\) The recent work of Field, Goldsmith, and Habing (1969), Spitzer and Scott (1969), Hjellming, Gor-
don, and Gordon (1969), and others indicates that the neutral hydrogen in the interstellar medium may
consist of two stable phases in pressure equilibrium. The existence of “hot” and “cold” phases could
give rise to additional multiple features. Certainly absorption by the cold component could be prominent
in the arm region. However, major emphasis in the present paper is placed on the rather natural occur-
rence of large-scale multiple features even in the presence of only one phase.
The observed profile is sketched only for the velocity range that corresponds to the Perseus-arm region. There is another peak, near G, that is observed outside this range near $v_{LSR} = 0$ km s$^{-1}$. This peak may be attributed to gas located very close to the Sun in the "Orion spur." Since the Orion spur, with a pitch angle of about 30°, is much more inclined than the two major arms on either side, it seems to form a cross-link between the Sagittarius and Perseus arms. As such, it does not appear as a prominent feature in the two-armed linear density-wave model or in the TASS model. It is possible that the Orion spur is simply another secondary feature of the type found in the TASS model in the outer regions of the disk.

Although the number-density and brightness-temperature profiles have a broad overall peak extending from E to F over a large velocity range of the order of 20 km s$^{-1}$, this does not necessarily mean that the gas which contributes to this velocity peak is spread over a large distance. On the contrary, the TASS model indicates that the 20 km s$^{-1}$ velocity spread between E and F corresponds to a spatial spread for the H I arm (Region B) of as small as 0.5 kpc, lying between 1.9 and 2.4 kpc from the Sun. On the other hand, if one were to interpret the profile by considering only the equilibrium Schmidt model, one would predict a spatial spread for the arm of about 2 kpc, lying between roughly 3 and 5 kpc. Therefore, the derivation of the spatial H I distribution according to the equilibrium model would not only produce an apparent broadening of the H I arm by an order of 2 kpc but also would make the H I arm appear much more distant (by an amount up to 2 kpc) than it may really be. Herein probably lies the reason for the spatial discrepancy in the Perseus-arm region between the optical arm and the H I arm, the latter of which is usually derived according to the equilibrium Schmidt model. Hence the TASS model suggests that the apparent discrepancy between the two arms is artificial and that the optical arm and the H I arm may very well coincide. Here the shock appears to be necessary to resolve this apparent discrepancy. Even with the linear density-wave model (dashed curve), this discrepancy between optical and H I arms is not resolvable. It is also quite evident that the 1970 Kerr map and the 1970 Weaver map for the distribution of neutral hydrogen over our Galaxy are quite different. However, it is important to note when the neutral-hydrogen data are interpreted through the TASS model that at least in the Perseus-arm region, $90^\circ < l < 200^\circ$, the noncoincident neutral-hydrogen arms of Kerr and of Weaver become one and the same arm which itself lies along the optical arm.

c) Results for Other Longitude Ranges

The TASS model has been examined in detail over the longitude region $90^\circ < l < 200^\circ$ in which practically all the available data for the Perseus arm exist. Over the whole region the results are similar. The results in a few other typical longitude ranges within this overall region will now be described.

i) $l = 110^\circ - 115^\circ$

Plotted in figure 4 are the theoretical curves of the TASS model and the observational data for the longitude range $l = 110^\circ - 115^\circ$. Although there are no interstellar-absorption-line data for this range, the data on the distribution of the young optical objects here make the shock appear rather essential. Neither the equilibrium Schmidt model (solid curve with crosses) nor the linear density-wave model (dashed curve) can account for those young objects with large negative velocities. The profile for $c = 3$ km s$^{-1}$ shows that it is really the dense gas just behind the shock region and the rarefied gas extending along a large distance over the velocity hill that are the primary sources for the large, slightly double, peak in the profile. Because the spiral arm is cut somewhat more obliquely along this direction than along the direction $l = 130^\circ - 140^\circ$, the velocity gradient just behind the shock is a little more gradual here. The more gradual the rise in velocity, the greater the proportion of gas that is distributed within each unit velocity interval behind the shock. Therefore, the shock (i.e., the dense gas just behind the shock) con-
Fig. 4.—Theoretical features of the 12° TASS model in the longitude range \( \lambda = 110^\circ-115^\circ \) (see legend to fig. 3).

ii) \( \lambda = 185^\circ-195^\circ \)

There is observational evidence favoring the continuation of the shock toward higher longitudes. In figure 5 the predicted curves of the TASS model and the observational data are sketched for the longitude range \( \lambda = 185^\circ-195^\circ \). Here the subcomponents of interstellar absorption found by Münch may be attributed to clouds just behind the shock. Again the shock appears essential to account for the absorption lines at the high negative velocities. In this longitude range the shock (i.e., dense gas just behind the shock), velocity hill, and secondary peak all contribute at about the same velocity to the one prominent peak in the predicted number-density and brightness-temperature profiles. For this reason, multiple subcomponents are not distinguishable in this longitude range.

d) Contour Map of Neutral Hydrogen Predicted in the TASS Model

Profiles of \( \text{H} \, \text{i} \) number density are calculated in the TASS model at 2° intervals over the longitude region \( 90^\circ < \lambda < 200^\circ \), and are combined to produce a theoretical neutral-
Fig. 5.—Theoretical features of the 12° TASS model in the longitude range $l = 185°-195°$ (see legend to fig. 3).

hydrogen contour map. Plotted in figure 6 is this theoretical contour map for the Perseus-arm region for the case with a mean turbulent-dispersion speed $c = 8 \text{ km s}^{-1}$. Contour levels of 10°, 20°, 40°, and 60° K are labeled. Superposed are the young optical objects taken from the observational data: O associations (O), O-B2 galactic clusters (Δ), and H II regions (■). Two typical gas streamtubes, a and b, as viewed instantaneously by an observer at the Sun, are also sketched: a with a mean galactic radius of 10-11 kpc, and b with a mean galactic radius of 11-12 kpc. To understand some general features of this contour map and to see why the young optical objects should occur where they do, we will first view these two typical streamtubes. At a longitude between $l = 130°$ and $l = 140°$ streamtube a meets the shock (Region A in fig. 3), and there the gas moving along streamtube $a$ suddenly feels a compression and its line-of-sight velocity jumps spontaneously from a velocity of about $-10 \text{ km s}^{-1}$ to a velocity at the shock ridge (dashed curve) of about $-50 \text{ km s}^{-1}$. Because the spiral arm is a trailing arm rather than a leading arm about the galactic disk, the outer streamtube b meets the shock at a higher longitude, $l > 200°$, than the inner streamtube a. Following streamtube a at low longitudes and streamtube b at high longitudes, we see that the gas in the compressed state at the shock ridge (Region B in fig. 3) undergoes a gradual decompression and moves up the "velocity hill" (Region C in fig. 3) toward a more positive line-of-sight velocity than that of the shock ridge. Near $l = 130°$ the velocity deviation of streamtube b from the...
Fig. 6.—Theoretical contour map of neutral hydrogen of the 12° TASS model: $90° < l < 200°$ for the case $c = 8 \text{ km s}^{-1}$. Solid curves are contour levels of 10° K, 20° K, 40° K, and 60° K. The two dot-dash lines represent two typical gas stream tubes (a) and (b). The "shock jump" corresponds to Region A in fig. 3. The "shock ridge" (- - - -) corresponds to Region B in fig. 3. The overall intense feature does not necessarily imply the presence of dense gas. Velocity effects and dense gas both contribute to this overall feature. An $\text{H} \text{I}$ maximum lies along the shock ridge (Region B in fig. 3). Although not as apparent in this case for $c = 8 \text{ km s}^{-1}$ as in the case for $c = 3 \text{ km s}^{-1}$, the effect of "velocity crowding" tends to produce the appearance of another $\text{H} \text{I}$ maximum (near $-40 \text{ km s}^{-1}$ for $l < 150°$), but this crowding of contour levels does not correspond to spatially dense gas and therefore does not represent a real $\text{H} \text{I}$ maximum. $\bigcirc$, $\text{O}$ associations; $\bigtriangleup$, $\text{O-B2}$ open clusters; $\blacksquare$, $\text{H} \text{II}$ regions. Since the young optical objects have only recently been triggered into existence from condensations of gas, the motion of these young objects is similar to the motion of the gas. These young optical objects are found to lie on the velocity hill (Region C in fig. 3) at somewhat more positive velocities than the velocity of the shock ridge.
shock ridge reaches a maximum, while that of streamtube \( a \) reaches a maximum only at a lower longitude \( l < 90^\circ \).

We can now visualize the total instantaneous picture of gas flow over the contour map by superposing streamtubes over the full range of radii. We will first direct our attention to the lower half of the contour map between longitudes of \( l = 100^\circ \) and \( l = 150^\circ \). The broad region of extremely weak intensity which encompasses velocities between \(-10\) and \(-30\) \( \text{km s}^{-1} \) is just the region of the shock jump (Region A in fig. 3) across which gas is decelerated so rapidly that only a small proportion of gas can possess a velocity inside. Because of the compression of the gas in the shock jump, rather dense concentrations of gas tend to "pile up" along the shock ridge (Region B in fig. 3) near \(-50\) \( \text{km s}^{-1} \). The shock therefore contributes to a narrow strip of high intensity along the shock ridge. Yet the overall feature of high intensity bounded by the 50\(^{\circ}\) K contour levels spans a rather broad range of velocity from \(-40\) to \(-60\) \( \text{km s}^{-1} \). The reason for such a broad feature lies in the fact that the shock ridge is not the only contributor; both the "velocity hill" (Region C in fig. 3) near \(-40\) \( \text{km s}^{-1} \) and the secondary peak (Region D in fig. 3) near \(-60\) \( \text{km s}^{-1} \) also contribute substantially. The positive-velocity edge of the feature near \(-40\) \( \text{km s}^{-1} \) corresponds to the top of the "velocity hill." Here the slope of the curve of line-of-sight velocity versus distance is so close to zero (see figs. 3 and 4) that a substantial amount of neutral hydrogen which is distributed spatially over large distances along the line of sight appears concentrated at this velocity.

At more positive velocities just above the top of the "velocity hill" very little gas is present. It is for this reason that the gradient of intensity is rather striking near \(-40\) \( \text{km s}^{-1} \) with considerable crowding of contour levels. This crowding of contour levels gives the appearance that an arm of rather dense neutral hydrogen is present. However, this appearance is altogether misleading. It should be emphasized that this unusually sharp rise in intensity is contributed not by dense gas but rather by a substantial amount of rarefied gas integrated over the top of the "velocity hill" (Region C in fig. 3) through a large distance along the line of sight. For even larger negative velocities beyond \(-60\) \( \text{km s}^{-1} \) the gas lies far from the shock, "velocity hill," and secondary peak (see fig. 3), and the number density has a much more gradual gradient with very little crowding of contour levels. At these large negative velocities the gas is quite rarefied. Over the upper half of the contour map between longitudes of \( l = 150^\circ \) and \( l = 200^\circ \) the overall intense feature spans a velocity range of comparable width. Just as at lower longitudes, gas in the compressed state lies along the shock ridge. Here the dense gas along the shock ridge is primarily responsible for the crowding of contour levels on the low velocity edge of the feature (e.g., near \( \nu_{ls} = 0 \text{ km s}^{-1} \) at \( l = 190^\circ \)). Since the "velocity hill" and secondary peak together form a rather extended plateau (near \( \nu_{ls} = 10 \text{ km s}^{-1} \) in fig. 5), they contribute substantially more than the shock ridge. For this reason, the shock ridge is shifted a little off the center of the overall feature at these higher longitudes.

We visualize the galactic shock wave as a possible triggering mechanism for the collapse of gas clouds leading to star formation along the spiral arm. Being triggered toward collapse along the shock ridge (Region B in fig. 3) and now beginning to evolve through their luminous stages of evolution some 5 to 50 million years later, the young optical objects move with the gas and are therefore predicted to lie on the "velocity hill" (Region C in fig. 3) at somewhat larger positive velocities than the velocity of the shock ridge itself. This strip is just the region where the young optical objects are found to occur over the entire longitude range in this contour map.

The theoretical contour map in figure 6 may be compared with the contour map of the observed data given by Lindblad (1967) which covers the full range of longitude \( l = 0^\circ-360^\circ \). A much more detailed comparison is possible with the contour maps of the observed data given by Rickard (1968) which span the longitude range \( l = 97^\circ-150^\circ \). This theoretical contour map seems to agree rather well with the contour maps of Rickard, although a good deal of unavoidable noise and irregularity is apparent in these...
maps of the observed data. The dashed lines sketched in Rickard's maps of the observed data represent what Rickard calls "distinct H i maxima." Extending roughly parallel to one another over a substantial longitude range, these "H i maxima" lie separated by a velocity of 10–15 km s$^{-1}$. At $\lambda = 135^\circ$, for example, Rickard sketches "H i maxima" at velocities of about $-40$ and $-50$ km s$^{-1}$. In view of the contour map for the TASS model a rather interesting interpretation of these "distinct H i maxima" exists. The H i maximum at velocity $v_{ls} = -50$ km s$^{-1}$ in Rickard's map corresponds to the shock ridge (Region B in fig. 3) and therefore the "real" H i arm in the TASS model. The other maximum sketched by Rickard at $v_{ls} = -40$ km s$^{-1}$ corresponds to the "velocity hill" (Region C fig. 3) where the effect of "velocity crowding" gives the appearance that a second distinct arm of H i exists, although in reality no such arm may be present. Thus, when interpreted through the TASS model, Rickard's dashed lines do not both represent real H i maxima; only the more negative one at the shock ridge corresponds to a real H i maximum and the real gaseous spiral arm.

Emphasis should also be directed to the region, or gap, of extremely low intensity which lies roughly between velocities of $-10$ and $-30$ km s$^{-1}$ over the entire longitude range in Rickard's maps. Henderson (1967) shows that this gap with a noticeably low intensity extends over a much larger longitude range and can be traced all the way from a longitude of about $I = 16^\circ$. When the velocity of this gap is converted to distance, it encircles almost the entire northern half of the Galaxy; and for this reason Henderson (1967) uses the term "negative arm" to describe this gap. On the 1970 Kerr map of the distribution of neutral hydrogen for our Galaxy, various places along this "negative arm" are labeled with the symbol L to show that its intensity is lower by at least one order of magnitude than that of the arms about it. An interesting interpretation of this "negative arm" arises through the TASS model. This gap that exhibits the "negative arm" in the observational data between velocities of $-10$ and $-30$ km s$^{-1}$ corresponds to just the region of the shock jump in the TASS model (see fig. 6). The TASS model automatically yields very little gas in this velocity gap spanning the shock jump (Region A in fig. 3). Hence, when interpreted through the TASS model, the "negative arm" is just a velocity effect arising from the rapid deceleration of gas across the shock.

The gas ridge found near $v_{ls} = 0$ km s$^{-1}$ in the theoretical contour map of the TASS model appears as a somewhat weaker feature than that in the maps of the observed data. This gas ridge (Peak G in fig. 3) is generally associated with the Orion spur in which the Sun is embedded. In the theoretical contour map only small amounts of gas are present here. The reason is quite simple. Because the Orion spur appears to be a secondary feature which may form a cross-link between the two major arms on either side, it is not a part of the TASS model that consists primarily of the two major arms.

V. THE TASS MODEL WITH 8° PITCH ANGLE

The TASS model is considered for a variety of cases in which the physical parameters $i$, $\Omega_p$, $F$, and $a$ take on different values throughout the parameter subspace outlined in § II. The systematic motion of the gas and the effective gas compression in the shock are governed by these physical parameters. A larger pitch angle $i$ for the spiral arms automatically implies a larger component of velocity normal to the shock and a larger systematic motion of the gas. Since the shock strength is proportional to the square of the Mach number of gas flow normal to an arm, a larger pitch angle also implies a higher shock strength. It is primarily the spiral gravitational field which drives the nonlinear gaseous response and causes the shock. The larger the spiral gravitational field $F$, the larger the systematic motion that can be produced and the higher the shock strength that can be maintained. A lower pattern speed $\Omega_p$ implies a larger net circulation of gas, $\Omega - \Omega_p$, relative to the rotating pattern, and this in turn induces a stronger nonlinear
response. The gas is dispersed through its kinetic and turbulent motions. A lower effective turbulent-dispersion speed \( a \) therefore causes a stronger response as well.

The pitch angle of the TASS model considered in Roberts (1969) was taken to be a constant of 8° throughout the galactic disk. Here the TASS model with 8° pitch angle \((\Omega_p = 12.5 \text{ km s}^{-1} \text{ kpc}^{-1}, F = 5 \text{ percent}, a = 8 \text{ km s}^{-1})\) is presented in the outer region of the disk and is shown to account for the observational data almost as well as the 12° TASS model. In figures 7, 8, and 9 the theoretical curves of this 8° TASS model and the observational data are sketched for the longitude ranges \( l = 110°-115°, l = 130°-140°, \) and \( l = 185°-195°, \) respectively. The contour map of neutral hydrogen predicted in the 8° TASS model is qualitatively identical to that of the 12° TASS model sketched in figure 6. It is entirely the effects due to smaller pitch angle \( i \) and lower field strength \( F \) that cause the systematic motion and the effective gas compression in the shock to be somewhat less in the 8° model than in the 12° model. While the compression of the gas in the shock in the 12° model is typically 12 times the mean density of the gas, the shock compression here in the 8° TASS model is about 6 times its mean value. The amount of compression is therefore reduced by about half by decreasing the field strength from \( F = 7.5 \text{ percent} \) to \( F = 5 \text{ percent} \) and the inclination from \( i = 12° \) to \( i = 8° \). A variety of other cases for different values of \( \Omega_p \) and \( a \) over the parameter subspace are considered.

Fig. 7.—Theoretical features of the 8° TASS model in the longitude range \( l = 110°-115° \) (see legend to fig. 3).
Yet, throughout the entire parameter subspace no other overall fit with observations is found to be any better than the 12° and 8° models presented here.

The theoretical curves of line-of-sight velocity for the gas in the 8° model coincide almost as favorably with the positions of the young optical objects as do the corresponding curves in the 12° model. The theoretical profiles of number density and brightness temperature for the 8° model coincide quite well with the observed profiles as well. Since the shock strength and the systematic motion are less in the 8° model than in the 12° model, multiple subcomponents in the profiles are not as distinguishable. For example, in the longitude range \( l = 130°-140° \), the shock, velocity hill, and secondary peak all lie within about 8 km s\(^{-1}\) of one another and therefore contribute largely to the same peak of the profile. The small plateau on the peak for the case \( c = 3 \text{ km s}^{-1} \) does, however, provide some resemblance to the observed double peak.

In view of the interstellar-absorption-line data the 12° model appears a little more attractive. In the 8° model the gas is not decelerated to negative enough line-of-sight velocity in the shock to account fully for all the interstellar-absorption-line data. This is evident in the longitude ranges \( l = 130°-140° \) and \( l = 185°-195° \). In these ranges the most negative absorption lines, in fact, lie below the dispersion band in which gas with a mean dispersion speed of 8 km s\(^{-1}\) is predicted to lie. In the 12° model this difficulty does not arise, and the interstellar-absorption-line data are easily accounted for.
An 8° TASS model with smaller $\Omega_p$ and $a$ and higher $F$ better accounts for the interstellar-absorption-line data, but its theoretical profiles of neutral hydrogen do not fit as well with the observed profiles as do those of the 8° model presented here and sketched in figures 7, 8, and 9. It is therefore difficult to make a definite optimal choice. Moreover, because of the possible uncertainty involved in the extrapolation of the equilibrium Schmidt curve the 12° and 8° cases, as well as a continuum of intermediate cases, should all be regarded as likely candidates. In view of the 12° and 8° cases, the real physical situation seems to be modeled well when the arm is inclined at a pitch angle anywhere in the range between 8° and 12°. Such a TASS model over this range seems to be necessary to account for the velocities of the absorption-line data relative to the velocities of the young optical objects along the Perseus arm.

VI. DISCUSSION

a) The Galactic Magnetic Field

A galactic magnetic field could permeate through the entire galactic disk. Roberts and Yuan (1970) constructed an 8° TASS model in which the galactic magnetic field was included. Now it is possible to extrapolate these results and determine the effect of introducing the galactic magnetic field into the 8° and 12° TASS models presented in

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the present paper without a magnetic field and for the outer parts of the disk. In this model the magnetic field passes roughly parallel to the spiral arms, and the principal spatial variation of the magnetic field is transverse to the arms. The magnetic force is dominated by the stress transverse to the field lines and behaves essentially as a hydrostatic pressure. As such, it contributes to the enhancement of the overall dispersion in the system and therefore tends to make the gas density compression as well as the systematic motion somewhat smaller. With a mean strength for the magnetic field of about 2–3 microgauss, the effective compression of the gas in the shock is typically about 4–8 times the mean density of the gas, instead of 6–12 times the mean value in the case without a magnetic field; and the magnitude of the systematic motion is about two-thirds of its magnitude in figures 3, 4, 5, 7, 8, and 9.

b) "Quasi-steady" Gas Flow in the Outer Parts of the Disk

After each revolution of the gas flow about the disk a gas streamtube in the inner parts closes upon itself by ending at approximately the same radius from which it began. Because only a negligible amount of nonclosure, if any, is present in the inner parts of the model, very little net radial transport of mass, momentum, or energy can take place. On the other hand, in the outer parts of the disk there is the tendency for a gas streamtube to wind inward toward the galactic center. The ends of a streamtube after one full revolution are separated in radius by a distance that is typically about 4 percent of the average radius from the galactic center. Here nonclosure is small but not negligible, and the net inward transport of mass, momentum, and energy is no longer completely insignificant. In this sense the TASS model is really a "quasi-stationary" model with "quasi-steady" gas flow, allowing some small amount of radial transport.

Also in the outer parts of the disk there is a tendency for the shock to bend slightly toward a smaller pitch angle than that of the background spiral arm. This effect becomes particularly evident at a radius of about 13 kpc where, in the 12° model, for example, the pitch angle of the shock is about 10° instead of the 12° adopted for the background spiral arm. The deviation of the shock from equipotential contours becomes more severe at larger radii. Since the numerical calculations are based on an asymptotic analysis which assumes that the physical perturbation quantities vary much more rapidly across equipotential contours than along them, the gas flow in the TASS model is perhaps a little less certain at regions beyond a radius of about 13 kpc. However, because the Perseus arm in the region 90° < l < 200° lies well within the radius of 13 kpc, the results and predictions of the TASS model are applicable to the Perseus arm.

c) Irregularity in the Perseus Arm

Because of assorted small-scale irregularities which are evident in the observational data, it is quite surprising that an ideal TASS model with a constant pitch angle throughout can provide as good an approximation to the real situation as it apparently does. In reality the interstellar medium is quite irregular, with strong small-scale perturbations in density and temperature. There is no doubt that such perturbations even on the small scale could influence small irregularities in the gas flow and the shape of the shock. The space distribution of the young optical objects in some regions indicates that the shock may deviate slightly from the ideal shock. For example, in the region at longitudes just beyond l = 200° the optical data indicate that the shock there may be a little less inclined and may lie a little closer to the Sun than the ideal 8° or 12° shock. Small-scale perturbations also influence the uniformity of compression along the shock. The spottiness of the newly born objects may in fact be a partial consequence of a nonuniform compression along the shock, which itself would act as a rather irregular triggering mechanism for the formation of these objects. Of course, the newly born objects con-

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dense from the most prominent perturbations which are themselves scattered randomly throughout the shock region, and therefore some spottiness of these objects would automatically be expected.

Absorption by dust can also distort the appearance of the actual distribution of the young optical objects. Along the Perseus arm moderate absorption could be expected to take place just behind the shock itself where the gas and dust are most concentrated. A prominent dust lane lying along the shock could conceivably blot out some of the young objects which were triggered into existence in passage through the shock and which now have migrated toward the far side of the arm beyond the shock and away from the Sun. The apparent scarcity of young optical objects between the longitudes of $l = 150^\circ$ and $l = 170^\circ$, for example, might be attributed to such absorption. Through his work on interstellar reddening in the vicinity of the Sun, FitzGerald (1968) did find that substantial interstellar absorption could be present in this longitude range.

d) Comparison with Other Models

The strongest evidence for a systematic motion (no longer regarded as a "peculiar" motion in this paper) is provided by the interstellar-absorption-line data, which show that part of the interstellar gas observed in front of large OB associations is departing systematically from circular motion and is approaching along the line of sight with speeds as high as 20 km s$^{-1}$. Münch (1957) suggested the possibility that locally expanding shells may exist around the young stars to provide components of absorption more negative than the velocities of the stars. These associations are at present rich in B-type supergiants, but some 20 million years ago they must have contained parent O-type main-sequence stars in considerable numbers. He reasoned that at the early stages of their development there were extensive H II regions which could have expanded the surrounding neutral gas. However, since velocities in excess of the isothermal velocity of sound in H II regions, around 10 km s$^{-1}$ (Spitzer 1969), are very unlikely, he realized the difficulty of explaining all the interstellar lines in this way. This type of expansion could be partly responsible for those lines that occur at velocities which lie close, perhaps within 10 km s$^{-1}$, to the velocity of the star.

Multiple subcomponents are often distinguishable, some occurring at or very near the velocity of the star and others occurring at velocities much more negative. It is difficult to account for more than one line at a time by the expansion of a shell. On the other hand, in the presence of a shock, gas clouds and interstellar absorption lines are possible at all line-of-sight velocities on the velocity hill, from the most negative value at the shock (Region B in fig. 3) to the velocity of the O association itself located near the top of the velocity hill (Region C in fig. 3).

In this paper it has been shown that the systematic motion encompasses a large-scale phenomenon along the entire length of the Perseus arm. However, this systematic motion has been termed peculiar motion by some authors mainly because it is most prominent in the small longitude range between $l = 100^\circ$ and $l = 140^\circ$ and as such it appears as a "peculiar" phenomenon over this local region. To account for this "peculiar" motion over the longitude range $100^\circ < l < 140^\circ$, Rickard (1968) suggested that the spiral arm in this part of the Galaxy is an expanding shell or ring. To produce a shell or ring so large as to encompass the entire region he proposed that an explosion occurred some 30 million years ago at about 2.9 kpc from the Sun toward $l = 120^\circ$ to cause the spiral arm to become an expanding ring. Since there is very little neutral hydrogen moving at velocities near $-20$ km s$^{-1}$ or at "positive" velocities relative to the center of his explosion, Rickard placed the position of the hypothetical explosion at the back edge of the arm. He then suggested that the material with "positive" velocities would no longer be visible, because no large mass of braking material is available and because the gas
would have moved away from the Sun to large distances. With the explosion on the back side of the arm he reasoned that only the material braked by the large mass of the arm would be visible, and this material would make up the negative velocity front edge of the "ring." The massive ring of $10^7 M_\odot$ encompassing the region $100^\circ < l < 140^\circ$, he postulated, is caused by one super-supernova, a small number of large supernovae, or a large number of ordinary supernovae. This postulated explosion seems to be a gigantic explosion in the ordinary sense. Furthermore, it is difficult to imagine how such an explosion could account for the systematic motion along the entire length of the Perseus arm over the longitude range $90^\circ < l < 200^\circ$. Not only would it have to be more gigantic still, but the exact location to cause such systematic motion is also a bit uncertain.

On the other hand, in the TASS model the supernovae which are distributed along the Perseus arm would be viewed as natural consequences of the triggering mechanism of the shock. Furthermore, it is easy to see why there should be very little neutral hydrogen moving at velocities near $-20 \text{ km s}^{-1}$. This is just the velocity range in which the shock jump occurs (Region A in fig. 3). With such sharp velocity gradients as are present in the shock jump, very little gas could be found at a given velocity per unit velocity interval in this gap (see figs. 3 and 6). Of course, the large negative velocities that Rickard explained by his expanding super-supernova are also completely accounted for in this paper over the full length of the Perseus arm by the systematic motion of the gas behind the shock (Region B in fig. 3).

**Secondary Arms in Our Own Galaxy**

The "spurs" and "feathers" often traceable in the outer parts of external galaxies as well as our own Milky Way system may be just secondary arms of the type found between the major arms in the TASS model. One such secondary arm is predicted to lie just a few kiloparsecs outside the Perseus arm. Although the optical data in figure 2 are quite scattered, most of the young objects can be associated with the major Perseus arm where the prominent shock occurs. However, there are a few young objects that lie several kiloparsecs beyond the major arm in the region where the secondary arm is predicted. These five or six young optical objects lie within a narrow band along the secondary peak that stretches from about $l = 150^\circ$ or even $l = 120^\circ$ all the way around to about $l = 200^\circ$. It is possible that this band of luminous objects could have been triggered into existence by the compression of gas in the secondary peak.

The second of the two secondary peaks found in the outer parts of the TASS model is predicted to occur in the region where the Carina spiral feature is observed to lie. If the Sagittarius and Perseus arms can indeed be regarded as the two most prominent arms that pass through the vicinity of the Sun, then the Carina feature might correspond to a secondary arm of the type predicted in the TASS model that lies between the Sagittarius and Perseus arms.

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