

75. LARGE-SCALE GALACTIC SHOCK PHENOMENA AND THE IMPLICATIONS ON STAR FORMATION

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Abstract. The possible existence of a stationary two-armed spiral shock pattern for a disk-shaped galaxy, such as our own Milky Way System, is demonstrated. It is therefore suggested that large-scale galactic shock phenomena may very well form the large-scale triggering mechanism for the gravitational collapse of gas clouds, leading to star formation along narrow spiral arcs within a two-armed grand design of spiral structure.

We have been reminded throughout this symposium that spiral galaxies have many irregular features, including multiple spiral arms; yet *two* principal arms making up a large scale grand design of spiral structure can often be traced to the central region and sometimes to the very center of these galactic systems. Often the spiral arms show a very high resolution into *knots* that are generally interpreted as HII regions and associations of stars. While the young stars practically always appear in stellar associations, the young stellar associations with their corresponding brilliant HII regions often occur in chains and spiral arcs similar to strings of beads within the larger grand design of spiral structure. In view of these observational studies, a basic problem stands out: namely, what physical mechanism could trigger star formation along a two-armed grand design of spiral structure in this orderly fashion.

The density wave theory has been suggested to account for the grand design feature. Yet, the presence of a marked grand design of spiral structure in many disk-shaped galaxies signifies an even more marked and narrow region for the initiation of star formation within the gaseous spiral arms of the grand design. In the density wave theory, this is indeed a very urgent problem to be explained; for, the gas stays inside the spiral arm for a relatively short period of time. Furthermore, in the linear theory, the gas concentration in a density wave extends over a broad region and could not be expected to provide a sufficiently rapid triggering mechanism to produce narrow spiral strips of newly-born luminous stars. We are therefore led to infer the presence of large-scale 'galactic shocks' that would be capable of triggering star formation in such narrow spiral strips over the disk, and we must therefore further refine the linear density wave theory by including nonlinear effects. In fact, we might expect self-sustained density waves in the gaseous component of the galactic disk to grow and develop in the course of time into disturbances with shock-like nature. Thus, the self-sustained density waves obtained by Lin and Shu in a linear theory (1964, 1966) might be expected in a nonlinear theory to develop into large-scale shocks with a regular two-armed grand design of spiral structure over the disk. Therefore, it is important to show that two periodically-located spiral shock waves present on the large scale

throughout the galactic disk are compatible with the general nature of a stationary nonlinear gas flow about the disk.*

The motion considered is that of the continuum of turbulent gas composing the gaseous disk, moving in a gravitational field consisting of a two-armed spiral field superposed on the Schmidt model for the Milky Way System. Suppose we now look at the asymptotic nonlinear solution for the gas motion we have obtained (Roberts, 1969). This nonlinear solution making up the gas flow picture over the galactic disk describes isothermal gas flow in closed, nearly concentric, and twice-periodic stream-tube bands that pass through a Two-Armed Spiral Shock pattern. Figure 1 shows this

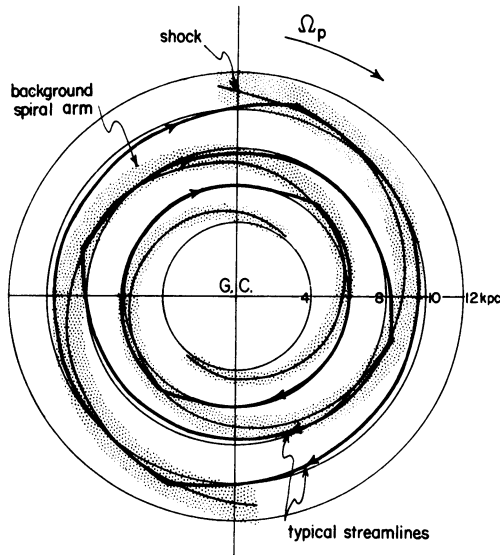


Fig. 1. Shock and background spiral pattern in the galaxy. Each arrowed gas streamline appears as a sharp-pointed oval with a sharp turning point at each shock.

simple model of gas flow, which I would like to refer to as the *TASS* picture – the *Two-Armed Spiral Shock picture*. Numerical calculations for regions between the radii of 3–4 kpc and 12 kpc in the Schmidt model confirm the compatibility of two periodically-located shocks lying along and within the imposed two-armed background spiral pattern. The background pattern may be regarded as the composite pattern of all the moderately-old stars of ages greater than perhaps 30 million years and therefore does not stand out in observational studies. Arrowed gas streamlines which turn sharply at each shock are sketched for several typical radii.

* Fujimoto actually carried out some nonlinear calculations on the gaseous component of the galactic disk as early as 1966. At that time it was difficult to construct a large-scale nonlinear gas picture for our Milky Way System; however his results nevertheless provided important insight for the initial stages of this work. A comparison of the basic differences between Fujimoto's work and the present investigation is given in Roberts (1969).

Suppose we focus our attention momentarily on a given streamtube. There are five basic independent parameters that govern the nature of the streamtube and the gas flow along it:

- (1) i the angle of inclination of a spiral arm to the circumferential direction, taken as about 8° ;
- (2) Ω_p the angular speed of the spiral pattern, taken as $12.5 \text{ km s}^{-1} \text{ kpc}^{-1}$;
- (3) F the amplitude of the spiral gravitational field taken as a fixed fraction, 5%, of the smoothed axisymmetric gravitational field;
- (4) ϖ the average radius of the streamtube; and
- (5) a the mean turbulent dispersion speed of the gas along the streamtube, taken in the range between 4 km s^{-1} and 10 km s^{-1} .

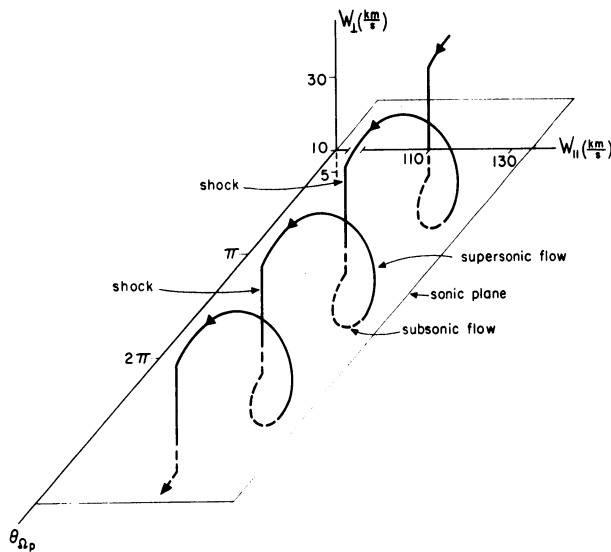


Fig. 2. The nature of gas flow along a typical streamtube.

Once these five parameters are specified the shock location with respect to the background spiral arm is automatically determined. Figure 2 illustrates the nature of the gas flow along a typical streamtube. W_{\perp} is the velocity component of gas across a spiral arm, and W_{\parallel} is the velocity component of gas along a spiral arm. The gas begins the same cycle again at every successive large-scale shock. The motion of the gas along a typical streamtube may be visualized in simplified terms as the nonlinear counterpart of epicyclic motion, as modified by gaseous 'pressure'.

This simplified interpretation is shown in Figure 3, which illustrates the radial motion of a gas particle in its epicyclic potential well centered at a fixed radius, ϖ_0 . Since the gas and the trailing spiral pattern travel about the disk at different angular speeds, where the angular speed of the gas may be much larger than the pattern speed, an observer travelling with the gas (at ϖ_0), would see one spiral arm, after another

spiral arm, travel past him toward the galactic center. At time $t=0$, the gas particle, the dark blob, is feeling the tendency to be dragged along by the gravitational field of the spiral arm, which is moving inwards faster than the blob. At a time roughly equal to half the period, the gas blob has been dragged inwards as far as its potential well will allow. After breaking away from spiral arm 1 and returning back across its potential well, it meets spiral arm 2 and shock 2. At this shock the gas particle begins the cycle once again.

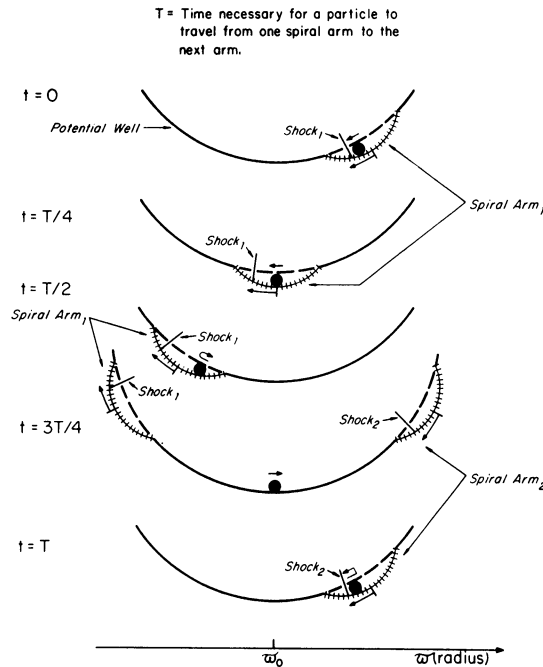


Fig. 3. Simplified interpretation of the radial motion of a gas particle in its epicyclic potential well.

Spitzer (1968) has considered a number of typical gas clouds and has concluded that the large clouds may not be far from the critical condition where gravitational collapse becomes possible. On the basis of Spitzer's investigation and the present results, it is now suggested that galactic shock waves may very well form the triggering mechanism for the gravitational collapse of gas clouds, leading to star formation. Since newly-born stars give rise to H II regions, galactic shocks may be visualized as the necessary forerunners of the prominent H II regions as well as the newly-born stars. In Figure 4, we view this possible star formation mechanism. Gas moves from left to right. Before reaching the shock, some of the large clouds and cloud complexes may be on the verge of gravitational collapse. A sudden compression of the clouds in the shock to perhaps five to ten times their original density could conceivably trigger the gravitational collapse of some of the largest gas clouds. As the gas leaves the shock region, it is rather quickly decompressed, and star formation ceases.

Attention may be focused on the narrowness of the gas density peak located adjacent to the shock. Such a narrow peak in density and pressure indicates appreciable star formation may take place only over the narrow spiral region lying just behind the large-scale galactic shock. Over the time period of 30 million years necessary for the formation and evolution of the relatively massive stars initiated at the shock, gas traverses a distance normal to the spiral arm of only about $\frac{1}{8}$ of the total wavelength separating successive arms. Therefore, the relatively massive and luminous newly-born stars initiated in the peak of gas concentration at the shock are confined to the inner side of the observable gaseous spiral arm of H I; for, when they pass outside this region, they no longer are newly-born or luminous. Since dust and gas travel together,

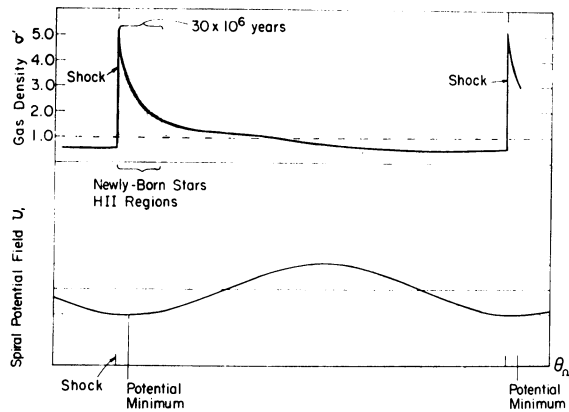


Fig. 4. Gas density distribution along a typical streamtube in the TASS picture. The potential minimum corresponds to the density maximum and the center of the background spiral arm.

the region for most prominent dust concentration also lies at the sharp H I peak adjacent to the shock. As the dust leaves the shock region, it is decompressed, and some of it may even be evaporated away by the newly-born stars and the H II regions, leaving lesser concentrations of dust to be found within and outside of the H II regions.

We can now visualize how this model galaxy may appear with large-scale shocks present. When observations of the galactic disk are made, the moderately-old star background distribution making up the imposed two-armed spiral pattern is not seen. Basically, what we do see are:

- (1) the observable gaseous spiral arms of H I, and
- (2) the newly-born luminous stars and brilliant H II regions.

Figure 5 illustrates this observable physical picture according to the shock predictions. A shock together with a sharp H I peak and a prominent dust lane occur on the inner edge of the observable gaseous spiral pattern of H I. On the inside of this observable spiral pattern (but just outside the shock and the sharp H I peak) lie the regions of newly-born stars and the H II regions. I think we can find general agreement here between this theoretical picture and observational studies of the Milky Way System by Morgan (this volume, p. 9), who showed some beautiful photographs of various

galaxies in which the locations of the newly-born stars, the luminous H II regions, and the prominent dust lanes occurred for the most part along narrow spirals. I should also like to mention the convincing agreement here with the observational studies of Beverly Lynds, presented at this symposium, who found in her studies of 17 galaxies that the most prominent dust lanes generally lie inside of the spirals of newly-born stars and the brilliant H II regions. There is also general agreement with the observational studies of Kerr *et al.* (1968), also presented at this symposium, who found that the luminous H II regions seem to lie just slightly off the ridge lines of H I in the sense

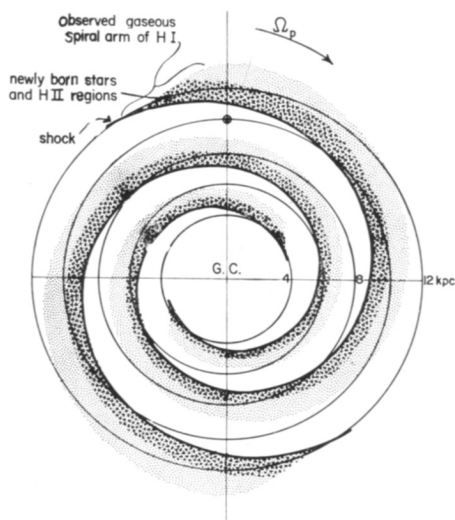


Fig. 5. The observable spiral pattern in the model galaxy.

of slightly larger radial velocity, or just slightly outside the sharp H I peak in our interpretation.

Suppose we now examine how the strength of the TASS pattern varies with radius from the galactic center. Figure 6 sketches the behavior of the gas density for stream-tubes at various radii. We first might note the peak representing the effective compression of the gas by the shock. This effective gas compression produced by the TASS pattern rises monotonically with decreasing radius from about 5 in the 11 kpc region to 8–9 in the 3–4 kpc neighborhood. It is the maximum value of gas density that likely suggests the actual degree of gas cloud compression and possibly the relative amounts of star formation and H II concentrations at various radii. Therefore, the TASS picture indicates a tendency toward greater star formation in the 4 kpc neighborhood. This feature of enhanced star formation and H II concentration toward the inner regions of the TASS picture shows general agreement with the observational evidence of Kerr and Westerhout (1965) and Kerr *et al.* (1968) for the mean H II distribution plotted with respect to radius over the galactic disk with the highest concentration of H II found between 4 kpc and 6 kpc.

Numerical calculations have been carried out over the disk out to the outer bound of 12–13 kpc where the TASS pattern terminates.

The TASS pattern rapidly diminishes in strength as we follow a spiral arm outwards from 11 kpc. Further out along the arm in the 12 to 13 kpc neighborhood, we visualize the TASS picture to merge into the density wave picture. Observational evidence for an outer cutoff of the TASS pattern appears in the observational studies of M. S. Roberts who found for a number of Sc-type galaxies that the circumferential bands with highest H I distribution do not coincide with and, in fact, lie significantly outside

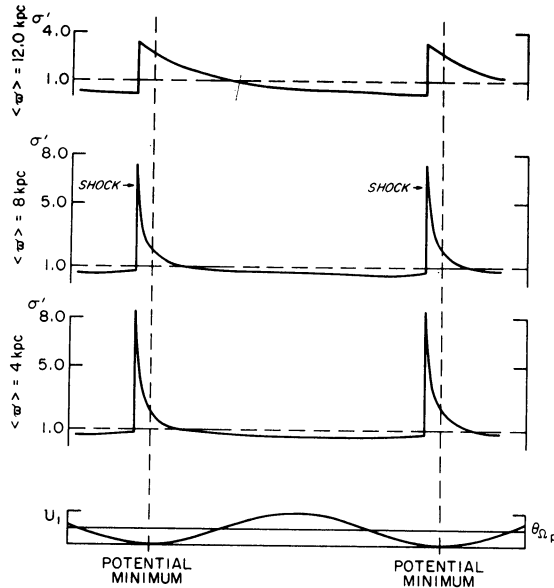


Fig. 6. Variation in the effective gas compression of the TASS pattern with respect to radius.

of the circumferential bands containing the most prominent newly-born stars and H II regions. For our own Milky Way System the same phenomenon seems to occur as illustrated by the Westerhout (1958) and van Woerden (Oort, 1965) results for the H I and H II distributions plotted with respect to radius over the disk, with the H II lying much interior to the H I. These observational results then seem to indicate a strong triggering mechanism that is capable of affecting the production of H II according to the mechanism's own pattern, considerably independent of the distribution of H I. This evidence then adds further support for a large-scale TASS pattern that can control to a large extent the star formation process as well as the radial distribution of H II over the galactic disk. Indeed, the reason why there may be no newly-born stars and no H II regions coinciding with the regions of highest H I distribution in our own Galaxy and in many Sc-type galaxies may be that there is no large scale shock pattern present at such large radii where the H I distribution is maximal.

I would like to end on one final note. The Two-Armed Spiral Shock picture seems to be capable of accounting for a good many striking features associated with the

grand design in many spiral galaxies, our own Galaxy included. On the other hand, we must not forget the many types of irregularities that often exist: such as the inter-arms branching across the grand design or the multiple sub-branches sometimes extending from a single large-scale spiral arm. There are no doubt many other types of irregularities as well, and perhaps not all are secondary effects. Yet at this stage, there is optimism about the TASS picture and the possibilities for its extension and refinement.

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