AN EJECTION THEORY OF SPIRAL STRUCTURE

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A number of questions was posed at this Symposium: why is the density of molecules highest near R = 5 kpc? Why is star formation most active near 5 kpc? The life-time of the molecular clouds near 5 kpc is about $2\cdot 10^8$ years - where does the gas come from? Why is almost no gas observed between R = 1 and 3 kpc?
It seems that an ejection theory can answer these questions.

The density wave theory of spiral structure is apparently a viable description of the physical state in our Galaxy between $6 < R < 16$ kpc (adopting the standard $R_\odot$ = 10 kpc). In this region the velocity variations due to the d.w. exceed those due to radial expansion, Δv(d.w.) $>$ Δv(ej.). There are, however, two basic problems the d.w. theory has to cope with: the importance of the d.w. in the presence of the very hot phase of the interstellar gas, and the excitation and maintenance of the d.w. in the presence of strong dissipative forces.

1. THE DENSITY WAVE THEORY AND THE VERY HOT INTERSTELLAR GAS COMPONENT

OVI lines detected by the Copernicus satellite and the soft X-ray background strongly indicate the existence of an extended component of the interstellar gas with temperatures in the range $3-10\cdot 10^5$K and densities in the range $5\cdot 10^{-4}$ to 10^{-2} cm^{-3} (McKee and Ostriker 1977). This very hot gas is believed to result from supernova shock heating (Cox and Smith 1974, Burnstein et al. 1976) and seems to pervade in the form of a network of tunnels and bubbles the whole space around the sun (within distances up to at least 300 pc). The filling factor is at least 0.5, it may be as high as 0.8. This means that the bulk of the volume is filled with a medium in which the sound velocity and hence the group velocity of shock waves is of the order of c_{II} = 120 km/s. The streaming velocities induced in the interstellar gas by perturbations due to the spiral d.w. are of the order $w_\perp$ = 10-25 km/s. Consequently strong shocks would never develop, and the d.w. theory would lose its most attractive feature, namely the spiral galactic shock which gave a theoretical basis for so many observational facts. Furthermore, the kinematic life-time of

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 147–150.

the d.w. becomes $\tau = \Delta R/v_g \simeq$ 10 kpc/120 km s^{-1} = $8\cdot 10^7$ yrs. This would deprive the whole wave concept of its sense since it was devised to overcome the winding dilemma implying just that time-scale.

A closer inspection, however, reveals that the interstellar medium is not in a steady state. The supernova shock heating is restricted to the spiral arms where supernovae light up, which are massive stars resulting from spiral shock-triggered star formation.
When the gas moves out into the interarm region the supernova activity subsides and the gas is efficiently cooling down to T = $1-3\cdot 10^4$K before it enters the next sweep of the d.w. pattern. The cooling time of the very hot gas is $t_c \simeq 10^5/n_e \simeq 10^8$ years (Shapiro and Moore 1976). The cycle time of the d.w. in a two-armed Galaxy is $t_{dw} = \pi/(\Omega_\odot - \Omega_p)$ = $2.7\cdot 10^8$ years. The supernova heating phase takes roughly 5-10 %, the inter-arm cooling most of the rest of this time. When the gas now enters the next sweep of the d.w. pattern the temperature is low enough to produce a strong shock with subsequent compression cooling, formation of low-temperature intercloud gas ($T=1-8\cdot 10^3$K), and cool gas and dust clouds part of which may later on collapse to form massive stars. After a few million years the most massive stars become supernovae and start the whole cycle again. It thus appears that the d.w. pumps non-gravitationally bound interstellar matter through a whole phase cycle which is schematically depicted in fig. 1. The Sun is in the local spiral arm located where maximal supernova heating is expected.
The overall sound velocity is about 17 km/s.
A detailed paper will appear in Astron. Astrophys. (Reinhardt and Schmidt-Kaler 1978).

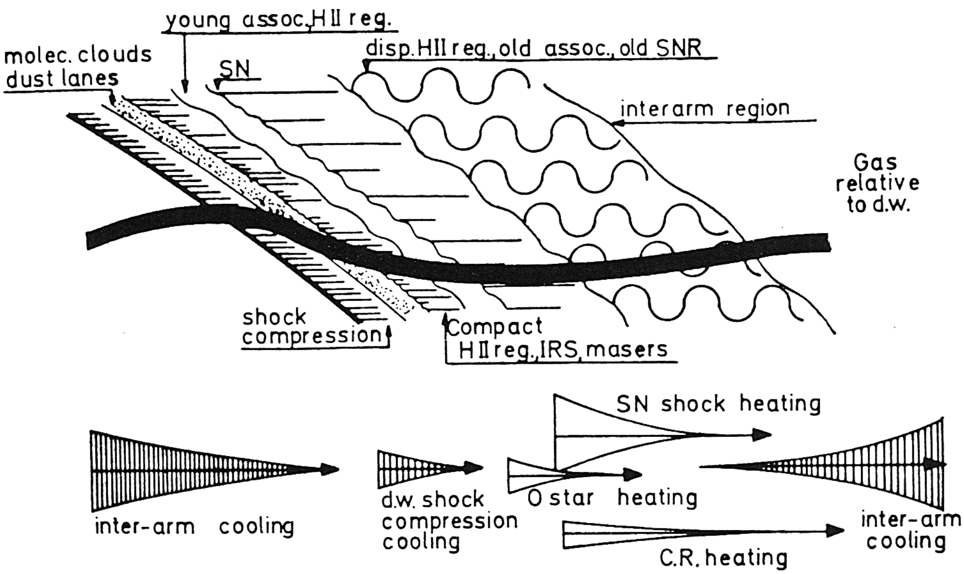

Fig. 1. The phase cycle of the interstellar matter due to the density wave half cycle. The most important cooling and heating processes in the successive phases are schematically indicated.

2. THE ORIGIN AND ENERGY SUPPLY OF THE DENSITY WAVE BY EJECTION OF GAS FROM THE CENTRAL REGION OF THE GALAXY

The total energy density of the d.w. in the corotating system is, according to Shu (1974) $\varepsilon_{dw} = 1 \cdot 10^9$ erg cm^{-2}, or within $3 \lesseqgtr R \lessgtr 15.7$ kpc the total energy is $\mathcal{E} = 7.1 \cdot 10^{54}$ erg. The kinematic life-time of the d.w. in our Galaxy is $\tau = \Delta R/v_g = 12.7$ kpc/17 km s^{-1} = $7.5 \cdot 10^8$ years; due to the energy used up by the galactic shock the dynamic life-time of the d.w. is still shorter (Feitzinger and Schmidt-Kaler 1978). In order to maintain the d.w. stationary it is therefore necessary to supply energy and angular momentum to the relevant regions of the Galaxy at least equal to

$$\dot{E} = \mathcal{E}/\tau = 3 \cdot 10^{38} \text{ erg s}^{-1}$$

$$\dot{I} = J/\tau = \frac{\mathcal{E}}{\Omega - \Omega_p}/\tau = 7 \cdot 10^{53} \text{ erg}$$

since the angular momentum in the corotating system becomes

$$J = \frac{m}{\Omega}E = \frac{2}{\Omega}E \cong \frac{E}{\Omega_p} \longrightarrow \frac{\mathcal{E}}{\Omega - \Omega_p}.$$

Lin's short wave mode propagates from the corotation radius to the Lindblad resonance circles. But since the d.w. energy is negative for $R < R_{CO}$ and positive for $R > R_{co}$ the SWM d.w. transports effectively positive energy and momentum from the inner to the outer Lindblad resonance.

The necessary energy supply cannot come from the outer regions. A central mass asymmetry, e.g. an oval distortion of the central spheroid or a bar could drive the d.w. (Schmidt-Kaler 1975). I was much pleased by the papers of Roberts and others who take up this idea which I put forward at Sydney 1973. But meanwhile our calculations showed a fundamental difficulty which is also observed in the work of Sanders, Roberts and others: the gas inevitably after the shock is braked and by the continuity equation gets a large component directed radially inward. Thus, the low-density gas shows expanding and the high-density gas ingoing motions which is just contrary to the observations. We do not invent particular scenarios to give explanations for each of the expanding features separately but take the observed expansion motions seriously in their entirety (Rohlfs and Schmidt-Kaler 1978). Also, the two other spiral galaxies whose inner regions have been investigated (M31 and M81) show strong expansion motions. In fact, the state of motion of M31 very much resembles that of our Galaxy (see fig. 2 for our Galaxy, and the work of Rubin et al., summarized by Schmidt-Kaler (1975) for M31). Mass outflow with typically $v_e = 100$ km/s, $\dot{M} = 0.25\ M_\odot$/year near $R_N = 2$ kpc will supply $\dot{E}_{kin} = \frac{1}{2} v_e^2 \dot{M} = 8 \cdot 10^{38}$ erg s^{-1}, $\dot{I} = \frac{1}{2} M R_N^2 (\Omega_N - \Omega) = 8 \cdot 10^{53}$ erg.

The mass and energy balance of gas shells lost by aging stars in the central spheroid is amply sufficient for continuous replenishment over th last $5 \cdot 10^9$ years (life-time of the disk population). Further: the mass loss of stars of the disk implies a net loss of kinetic energy and an

https://doi.org/10.1017/S0074180900014352 Published online by Cambridge University Press

increase of gravitational energy which leads to cooling of the disk and stabilizing of the spiral wave.

The oval distortion of the central spheroid may be described by the Riemann instability (Schmidt-Kaler 1978): Model calculations show that explosions in the nucleus with energies of the order of 10^{54} erg on a time-scale of 10^6 yrs can produce the observed situation.

Summarizing, the ejection theory
(1) relates spiral development to activity of galactic nuclei
(2) predicts two, diametral, trailing spiral arms (inside $R = R_{iL}$) which in turn excite trailing d.w. spirals for $R > R_{iL}$
(3) explains by the continuity equation the gas densities (and ensuing processes) inside R = 6 kpc.

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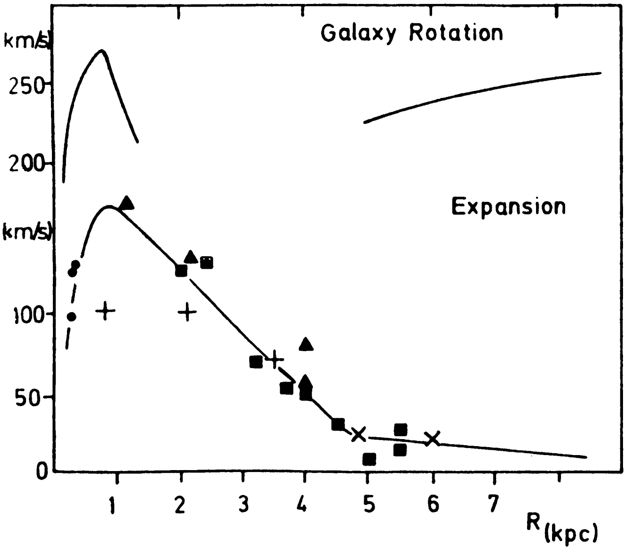

Fig. 2. The velocity curve of our Galaxy (circular component according to Sanders and Lowinger 1972, radial component according to Schmidt-Kaler 1978). The features of Cohen and Davies are partly at $|z| > 150$ pc so that apparently too small expansion components may result

- ● molecular lines
- × optical data
- ■ older data
- ▲ Rohlfs+Schmidt-K.1977
- + Cohen+Davies 1976

https://doi.org/10.1017/S0074180900014352 Published online by Cambridge University Press