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On the Formation of Interstellar Cloud Complexes, OB Associations and Giant H II Regions

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Summary. We propose that large cloud complexes, OB associations, and giant H II regions form as a result of the initiation of the magnetic Rayleigh-Taylor instability in the interstellar medium by the passage of a galactic shock. Total masses of about $10^6 M_{\odot}$, formation of unbound systems, and alignment along spiral arms with typical separation of about 1 kpc are natural consequences of this point of view. In addition, we argue that the enhancement of synchrotron radiation to be expected in the compression zones of spiral galaxies has hitherto been considerably overestimated.

Key words: instability – spiral arms – cloud complexes – giant H II regions

I. Introduction

In this paper we consider a mechanism which may offer a comprehensive explanation for the following well-known facts concerning OB associations and giant H II regions.

a) The total mass of a large OB association in our own galaxy, if we include the associated H II regions and the neighboring H I cloud complexes, may exceed $10^5 M_{\odot}$ (Raimond, 1966); but it may exceed $10^6 M_{\odot}$ in certain Scd galaxies like M 33 (Israel and van der Kruit, 1973) and M 101 (Goss, private communication). The discrepancy in masses is partially due to the difficulty in recognizing the true extent of very large associations in our own galaxy (see, e.g., Blaauw, 1964).

b) Observational evidence indicates that the aggregate of stars in a typical association constitutes an unbound system and is in a state of expansion (Ambartsumian, 1947). If such a system has formed from some yet more diffuse distribution of matter and if no significant loss of binding mass occurred, self-gravity *alone* cannot account for its formation.

c) Observations also show that giant H II regions often line up in narrow lanes along spiral arms (Morgan, 1970) almost like "beads on a string". Occasionally their spacing *along* the "string" is remarkable for its regularity. In other galaxies, particularly irregulars, the distribution of H II regions is much more chaotic, and there is some evidence for "bursts of star formation" separated typically by distances of about 1 kpc (Hodge, 1970).

In the case of spiral galaxies we propose that the mechanism which accounts for the above phenomenon, (see also Pikelner, 1970) is the triggering of Parker's (1966, 1967) instability by a spiral shock wave. Such shocks (Fujimoto, 1966; Roberts, 1969; Shu *et al.*, 1973; Woodward, 1973) develop from nonlinear gas flow in the spiral gravitational field of the density-wave theory (Lin *et al.*, 1969). We begin our discussion by examining the effect of a spiral wave on an interstellar medium consisting of a thermal gas, a cosmic-ray gas, and a large-scale magnetic field frozen in the matter.

II. Large-scale Physical Picture

The interstellar medium in the interarm region, prior to passage through a galactic shock, is likely to be threaded by a relatively weak magnetic field (Roberts and Yuan, 1970; van der Kruit, 1973a-c), and it may also contain two distinct thermal phases (Pikelner, 1967; Field *et al.*, 1969; Spitzer and Scott, 1969). Shu *et al.* (1972) view the interarm gas as consisting of discrete, warm H I clouds that are in rough pressure equilibrium with a hot, tenuous, intercloud medium. The small-scale structure of the thermal gas may be ignored for scales larger than about 10^2 pc. Thus, for the moment, we lump the cloud and intercloud phases together, and we consider the response of the composite medium as it passes through a galactic shock. The average density of this composite medium will be referred to as the *space density* of the interstellar gas. (In § III, where we discuss star formation, we find it necessary to consider the small-scale structure of the interstellar gas.)

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We denote the ratio of the magnetic to gas pressure by α. If we ignore, for the time being, the degree of freedom provided by the vertical direction, the nonlinear flow calculations lead us to expect that α will typically vary from about 1/3 in the interarm region to about 3 behind the galactic shock[1]).

In the limit of very small α, Parker's instability corresponds to convection rather than to accumulation of gas into clumps (Shu, 1974). Since α is moderately small in the interarm region, the development of Parker's instability there is likely to lead to convective turbulence, to inflation of field lines by cosmic rays, and to the formation of a fat radio disk (see also Parker, 1969). In the environment pertinent to interarm regions, we do not expect gas drainage along field lines to form clumps of interstellar gas whose lifetimes would be appreciably longer than the dynamical timescale associated with the vertical motions, $\omega_z^{-1} \sim 10^7$ years. The effects of the differential rotation of the galaxy would only reinforce this conclusion.

Upon compression by a galactic shock, the increase in the magnetic field $\boldsymbol{B}$ would initially be directly proportional to the compression of the surface density, σ. This means that α would initially increase as σ because in effect the compression of the interstellar gas occurs isothermally. However, a sudden increase of α to values of about unity destroys even the large-scale balance of forces in the vertical direction, and it also shortens the critical wavelength for the onset of the magnetic Rayleigh-Taylor instability, which may thus be initiated. This leads to drainage of thermal gas along field lines under the action of the vertical gravitational field of the galaxy, and to the formation of large condensations of gas at the position of magnetic field "valleys". At the same time, the unloaded portions of the field lines tend to buckle in the vertical direction. (See the equilibrium states for this problem calculated by Mouschovias [1974].) The net result is to relieve the magnetic stresses which led to the onset of the instability in the first place and to prevent the increase in the strength of the magnetic field from keeping up with the increase in the surface density of the thermal gas. In fact, we suspect that a large-scale average performed over the width of the compression region and over one "Parker wavelength" (~ 1 kpc) along a spiral arm – this average to be denoted by angular brackets – leads to the relation $\left\langle \int_{-\infty}^{\infty} B^2 dz \right\rangle \propto \langle\sigma\rangle$ unlike the model of Roberts and Yuan (1970) in which $\left\langle \int_{-\infty}^{\infty} B^2 dz \right\rangle \propto \langle\sigma\rangle^2$. "Equipartition" on a large scale, based on the assumption that the magnetic field is confined to the galactic disk by the weight of the interstellar gas, has also been advocated by Parker (1969). We caution, however, that α itself varies appreciably from point to point since the drainage of gas along the field lines which are highly deformed is very efficient (Mouschovias, 1974).

We note here that differential rotation (or more precisely, the differential motions along neighboring streamlines) will tend to suppress disturbances which have long radial wavelengths (the radial direction being perpendicular to the unperturbed magnetic field). The time required for shear to distort the shape of a material body significantly is one-half of the reciprocal of Oort's constant A, i.e., only about 3×10^7 years in the solar neighborhood. For Parker's instability, the relevant length scale in the radial direction is that over which the differential motion due to shear is comparable to 2π times the hydromagnetic wave speed. Shu (1974) has shown that differential rotation has little effect on the growth of disturbances whose radial wavelengths are much shorter than this characteristic length, as long as their wavelengths *along* the field are sufficiently large. The maximum growth rate occurs for wavelengths along the magnetic field which are approximately equal to 2π times the initial vertical scale-height (for $\alpha \cong \beta \cong 1$). The galactic shock of the density-wave theory provides a natural way of producing disturbances having wavelengths very small across the magnetic field (approximately the radial direction) and quite large along it. In this picture, we expect the gaseous spiral arm, defined by the postshock region, to break up along its length into large condensations of gas, each having horizontal dimensions of a few hundred parsecs and a total mass of the order of $10^6 M_\odot$. The separation between condensations along the arm is expected to be roughly equal to 1 kpc.

Mouschovias (1974) has determined two-dimensional final equilibrium states for the system of interstellar gas and field, in which Parker's instability has developed[2]). These final states represent large-scale condensations of the interstellar gas having fairly diffuse boundaries. The regions of high and low gas density exhibit a contrast in vertical column densities (as well as in emission measures) of about 2 or 3 to 1. Moreover, the maximum volume density of gas in a typical final state is very nearly equal to the maximum density in the initial stratified state, because of the imposed reflection symmetry about the galactic plane. If stars are to form within such gas condensations, their formation should depend on the existence of small-scale structure within the large-scale condensations (see § III).

The whole medium eventually re-expands into supersonic flow well downstream from the galactic shock.

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[1]) This estimate assumes that the magnetic field $\boldsymbol{B}$ varies directly as the surface density σ of the thermal gas; we shall see below that this assumption breaks down in the compression zones of the galaxy because of "buckling" of the field lines in the vertical direction.

[2]) Since both the distortion time and the decompression time ($\sim 3 \times 10^7$ years) are longer than the e-folding time ($\sim 1 \times 10^7$ years) of the most unstable disturbance, there is enough time for the system to reach these final states.

This expansion increases the spacing of the gas condensations formed in the compression stages and decreases the absolute value of the magnetic pressure as well as its value relative to the gas pressure. Together with the shear of the differential rotation of the galaxy, these processes tend to restore the medium between spiral arms to a "turbulent" state with weak magnetic fields, with considerable inflation of field lines by cosmic rays, and with a much smaller degree of large-scale structure. In particular, we would imagine that the massive condensations of gas would be redispersed.

Here it is important to realize that although supernova explosions and expanding H II regions cannot impart sufficient momentum to disperse gas condensations which have masses of the order of $10^6 M_\odot$, these condensations are easily pulled apart by the effects of differential rotation. Note also that the low space densities typical of these condensations imply that they are not gravitationally bound against the effects of galactic rotation and internal dispersive velocities (relevant formulae can be found in Toomre, 1964 and Goldreich and Lynden-Bell, 1965). Thus, we do not expect large condensations of gas to form in the interarm region before the magnetic Rayleigh-Taylor instability is triggered at the next galactic shock.

III. The Formation of OB Associations

Since the gas condensations produced by Parker's instability are large, diffuse structures, it is implausible that the instability would, by itself, trigger star formation. For gravitationally bound objects to form, we invoke the presence of small-scale substructures of relatively dense material. We identify these with the "ordinary interstellar clouds" [which in the model of Shu *et al.* (1972) have been decompressed to densities of about one atom per cubic centimeter in the interarm region]. Thus, we think of the interstellar gas as consisting of clouds embedded in a hot tenuous intercloud medium, and we associate the vertical scale-height of the distribution of interstellar clouds with their random space motions. The development of the large-scale magnetic Rayleigh-Taylor instability in this patchy interstellar medium results in a gathering of clouds into very large *cloud complexes*. From the difference in "potential" energies between final and initial states calculated by Mouschovias (1974), we estimate that the kinetic energy associated with the motion of clouds would increase only slightly as a result of their downward motion along field lines. Thus, the r.m.s. velocity dispersion of clouds in a cloud complex will remain close to typical interstellar values.

While the composite medium experiences the magnetic Rayleigh-Taylor instability as it passes through the galactic shock, the individual clouds will be imploded by shocks driven into them partially by the higher pressure of the ambient intercloud medium and partially by the dynamic pressure of their motions relative to that medium. This process has been described in a preliminary manner by Shu *et al.* (1972) and is currently being investigated in detail by Woodward. Eventually some of these clouds may become gravitationally bound and collapse to form clusters of OB stars. In summary, clouds are compressed (some to the point of collapse) by passage through a galactic shock and tend simultaneously to accumulate in magnetic field valleys because of the development of the magnetic Rayleigh-Taylor instability. These are two independent physical processes, and therefore the final appearance of several subgroups of OB stars of different ages within a given OB association (Blaauw, 1964) would be a natural consequence of this picture. Note, moreover, that the process of large-scale clumping does not leave the regions between condensations empty so that we expect to find some small clusters of OB stars which do not belong to massive associations.

The time scales for the collapse of individual interstellar clouds and the development of Parker's instability are about equal ($\sim 10^7$ years); however, some rough estimates and preliminary calculations (Woodward, unpublished) indicate that the collapse of some clouds would occur sufficiently rapidly that they would individually become quite dense while still being collected in magnetic field valleys under the action of the vertical gravitational field of the galaxy. Aggregation of the clouds by these *external* forces explain, then, the final appearance of an OB association which has an expansion velocity of 5–10 km/s. This velocity dispersion represents mainly the original velocity dispersion of the distribution of interstellar clouds. At no stage of the clumping process does the aggregate of clouds become a gravitationally bound entity; thus, the association is rather easily dispersed at a later stage by the differential rotation of the galaxy, as was originally envisaged by Bok (1934).

It is a well-known fact that OB stars are better confined to the galactic plane than the distribution of H I gas (Blaauw, 1965). Contrary to common expectations, this could not have resulted in a simple way from the development of Parker's instability since Mouschovias (1974) has calculated that in the final state the scale height of the gas at the position of magnetic field valleys is larger than the scale height of the gas in the initial stratified state. The thinner distribution of OB stars can be understood if the rate of star formation varies as a power of the space density of the gas that is larger than unity (Schmidt, 1959). Such a dependence occurs in a natural way in our model: One factor of space density follows simply from the greater concentration of raw material available for star formation close to the galactic plane. A further (positive) dependence on density follows from the reasonable assumption that a greater *fraction* of the existing clouds would be brought to collapse in regions of higher ambient pressure (and higher space density). An exact estimate of the latter effect would depend on the detailed distribution of cloud masses, but if the critical cloud mass for gravitational collapse depends rather sensitively on the external pressure (cf. Shu *et al.*, 1972), the effect will be significant.

The ionization zones produced by many OB stars in the large-scale condensations of interstellar gas can be identified with giant H II regions. The appearance of giant H II regions lined up as "beads on a string" along spiral arms can therefore be attributed to a narrow zone of high gas compression behind a galactic shock, which provides the "string", and the development of the magnetic Rayleigh-Taylor instability, which breaks up the arm along its length into many "beads".

Using energy considerations, Mouschovias (1974) points out an advantage for the "beads" to coalesce. Considerable time, free of disruptive influences, is required if coalescence is to occur; thus, we would expect very large gas concentrations to have a chance of forming only in galaxies with little differential rotation. This may be an explanation for the enormous concentration of gas observed on the southern side of M33 (Wright *et al.*, 1973). The zones of high gas compression in galaxies with weak differential rotation have a tendency to be rather broad in the radial direction (Shu *et al.*, 1973; Woodward, 1973), and the spatial arrangement of the giant H II regions would then be much more chaotic looking.

IV. Enhancement of Nonthermal Radiation

Piddington (1973) has criticized the density-wave interpretation of spiral structure on the grounds that very large enhancements of nonthermal radiation would be predicted in the postshock region, whereas only moderate enhancements have actually been observed (cf. Mathewson *et al.*, 1972; van der Kruit, 1973a-c). The difficulty lies in the assumption made by Piddington and Mathewson *et al.* namely, that the compression occurs in a rectilinear one-dimensional fashion. First, we have already argued in § II that, unlike the one-dimensional compression, the relief of magnetic stresses by buckling in the vertical direction would lead to an increase in the magnetic field that is less than directly proportional to the increase in the surface density. Second, the tendency for the cosmic-ray pressure to distribute itself uniformly along magnetic flux tubes (see, e.g., Shu, 1974) means that, after Parker's instability develops, most of the relativistic particles will be found in the regions where the field is weak, i.e., in the inflated portions of the field lines. The net effect implies that the enhancement of synchrotron radiation in the spiral arms of a galaxy viewed face-on should be considerably below the factor $\langle\sigma/\sigma_0\rangle^{2.7}$ estimated by Piddington (1973) and Mathewson *et al.* (1972). (The quantity σ_0 denotes the surface density averaged over both the arm and interarm regions.)

We make one final comment on this topic. To reconcile theory and observations in M51, Mathewson *et al.* adopted a reasonable model with two components of the nonthermal radiation – a thin disk component which reflects directly the compression associated with the spiral structure, and a fat disk component which does not. This view is equivalent in some sense to the role we attribute to "buckling"; only in our picture, we would identify Parker's instability as the physical mechanism (operative in both the arm and the interarm regions) which is responsible for the formation of a fat radio disk.

V. Discussion

Although galactic shocks are not necessary for initiating star formation – any mechanism that provides sufficient compression, such as supernova explosions, may suffice to set a nearby cloud into collapse – we believe that the spiral wave shapes dramatically the local environment in which various small-scale processes occur. An important consequence of including the interstellar magnetic field in the picture is that Parker's instability may be triggered by the passage of the interstellar medium through the galactic shock. We have argued that the result of the onset of this instability in spiral arms is the accumulation of gas in large-scale condensations, within which gravitationally unbound OB associations can form. The characteristic spacing of the condensations along spiral arms is approximately equal to 1 kpc.

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