HYDROSTATIC EQUILIBRIUM OF GAS-FIELD SYSTEM IN THE GALAXY AND ITS STABILITY

S.A. STEPHENS
Tata Institute of fundamental Research
Homi Bhabha Road, Bombay 400005, India

ABSTRACT. The stability of the gas-field system in the Galaxy is examined to show that it is difficult to maintain a stable configuration due to numerous energy releasing phenomenon occurring in the Galaxy. However, it is argued that, as in the case of our atmosphere, hydrostatic equilibrium is expected in the Galaxy on a global scale. A summary of the advances made in the study of the global equilibrium is presented. The major postulates and predictions from some of these studies are compared with the observations. The usefulness of detailed observation of nearby edge-on galaxies in radio and X-ray regime is brought out.

1.INTRODUCTION

Interstellar gas, magnetic field and cosmic rays are coupled to each other in the Galaxy. They interact among them exchanging energies. Cosmic rays being charged particles, are tied to the magnetic field, which is confined to the gas due to the ionized component. The gas is attracted towards the plane by the gravitational potential, which results from the distribution of stars and matter, both seen and unseen. In the plane of the Galaxy effects due to galactic rotation, spiral density wave etc. would further complicate this coupling. While these effects are not very important away from the galactic plane, phenomenon such as infalling of gas, galactic wind may influence the dynamics of the system.

The important role played by the magnetic field and cosmic rays in the dynamics of the gas-field system was emphasized by Parker (1966, 1969) two decades ago. Progress in this field is rather slow over these years mainly due to the lack of observational tests to many of the theoretical expectations. In this review I briefly introduce the general problem with a simple approach and examine the stability of the gas-field system. It appears that there can be no stable system. The consequences of these instabilities are many including the formation of cloud complexes and small scale turbulences. However, it is expected that globally the system should be in a state of hydrostatic equilibrium. The advances made in this field are briefly discussed and the results from such studies are summarized. Though observational tests for these

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 323–332.

models are difficult to realize, some of the predictions are compared with the available observations. They provide the description of the present state of art in this field of research and help us to see what can be done in the future to have a greater understanding of the gas-field system.

2. STABILITY OF THE GAS-FIELD SYSTEM

Hydrostatic equilibrium of the gas-field system perpendicular to the galactic plane (z-direction) can be described by the well known relation (Parker, 1969) between the internal pressure of the system and the gravitational force, as given by

$$d[P_G(z) + P_{MF}(z) + P_{CR}(z)]/dz = -\rho(z)g(z) \qquad 1$$

Here, P's are the pressures due to gas (G), magnetic field (MF) and cosmic rays (CR), ρ is the density of gas and g is the acceleration due to gravity. The total internal pressure $P_T = P_G + P_{MF} + P_{CR}$ is given by the integral

$$P_T(z) = \int_z^{\infty} \rho(z)g(z)dz \qquad 2$$

Parker considered a simple case in which z distributions of all three components of the internal pressure are similar, such that $P_{MF} = \alpha P_G$ and $P_{CR} = \beta P_G$ and the gas is isothermal. For a constant value of g(z), the distribution of gas, MF and CR is exponential with a scale height $H = (1. + \alpha + \beta)u^2/\langle g\rangle$, where u is the rms velocity of the gas.

This simple hydrostatic equilibrium state was tested for stability by Parker(1966) using two dimensional perturbation of the type $\exp(ik_y y + ik_z z)$, where k is the wave number and the direction of y is parallel to the initial MF in the plane. He had shown that the above perturbation can lead to instability if the adiabatic index γ of the composite fluid satisfies the relation

$$\gamma < 1. + \beta + \alpha[0.5 - 8.0(k_y^2 + k_z^2)H] \qquad 3$$

For small values of k, the above relation becomes $\gamma < (1. + \beta + \alpha/2.)$. It can be seen that for large values of k_y, the system is stable against perturbation due to the tension in the field lines. On the other hand, instability arises at long wavelengths due the slackness of the field lines. As a result thermal gas slides down along the field into the depressions, which in tern makes the field lines rise further due to CR pressure. The fastest growing instabilities are triggered by three dimensional perturbations with $(1. / k_x) \ll H$. The reason for this growth of instability is as $k_x > k_y$, the raised portion of the magnetic field expand into the room available by the depression of lines on either side. This kind of instability would generate small scale turbulences.

Shu(1974) examined Parker instability in some detail by including differential rotation with an axis perpendicular to the magnetic field lines. He concluded from his analysis that no finite amount of shear and rotation can stabilize the system. On the other hand, Mouschovias(1974, 1975) argued that, even for small k_y perturbations, the inflation can not continue for ever. The flux tube will be highly deformed and the inflation will be arrested when the tension in the field lines becomes the major confining force of CR. Cosmic rays can only hasten the initial inflation, but at the latter stages the CR pressure gradient becomes small as the CR density decreases with the expansion of the MF. He had shown that the ratio of the MF to CR pressures becomes proportional to $H^{.333}$. The greater the inflation, the larger the value of H and thus CR will not overwhelm the field. However, the main assumption in the above argument is the conservation of CR particle number in a flux tube. It was pointed out by Cesarsky (1980) that the above assumption need not be correct because of the possible presence of CR sources which continues to inject CR into the flux tube during the period of inflation.

The instability criteria derived by Parker can not be used in a situation, in which α and β are functions of z. Using hydrodynamic energy principle, a more general criteria for testing the instability was derived by Lachieze-Rey et al (1980). They showed that the critical adiabatic index γ_c for stability should be

$$\gamma_c = -\Gamma P_G(z)/P_{CR}(z) + \rho^2 g(z)/P_G(z)(d\rho(z)/dz) \qquad 4$$

where Γ is the polytropic index for CR. When $\gamma < \gamma_c$, the system becomes unstable . If CR re-distributes rapidly along the field lines, Γ = 0., otherwise it could be as large as 4/3. From the above equation one notices that the polytropic behaviour of CR tends to stabilize the system. Therefore, the maximum value of the critical adiabatic index would be without the first term in Eqn.4.

The growth rate of these instabilities are of particular interest in the understanding of these dynamical effects. In the simple model of Parker, the instability grows in time scale comparable to the free fall time of the gas over one scale height. This is about $H/c_s \sim 10^7$ yrs, where c_s is the the sound speed. Zeweibel and Kulsrud (1975) examined the effect of including microturbulent magnetic field produced by cloud motion and showed that the entangled magnetic field acts as a viscous fluid and tends to stabilize the system. As a result, the growth time becomes longer by an order of magnitude. A generalization of the above derivation was carried out by Lachieze-Rey et al (1980), who derived the growth time for the horizontal equilibria of Badhwar and Stephens (1977). The values obtained for those states, which were found to be unstable, are in the range of a few times 10^7 yrs.

It is interesting to note that these growth times are of the order of a few tens of million years and appear to be rather very large. If one consider supernova explosion of once in 20 yrs in the Galaxy, a total of 1.5 million explosions are to take place over a surface area of 700 kpc^2 during 3×10^7 yrs. Taking an approximate size of (100pc)^2 for the surface area of an instability, about 20 supernovae are exploded during the growth period. Numerously more small scale energy releasing phenomena such as, novae, star formation and stellar winds from OB associations are taking place throughout the Galaxy. These are to be considered in examining the growth pattern of instabilities, and to see how these activities trigger instabilities and drive those already initiated either by small perturbations or by violent events. It is clear to me that instabilities can not be avoided and 'there is generally no complete stable equilibrium state for a gas-field system confined by gravity'- Parker (1969).

3. STUDY OF HYDROSTATIC EQUILIBRIUM

Our experience of living inside the Earth's atmosphere tells us that the atmosphere is always in a unstable state locally. There are disturbances from small to large scale, both in extent and in intensity. However, the atmosphere is in a state of global hydrostatic equilibrium. The locally induced non-equilibrium conditions, though appear to be violent at times, are not strong enough to disturb the gross equilibrium state. Therefore, it is natural to expect that the gas-field system in the Galaxy to be in a global equilibrium state. One may also make a note that the time scale for the growth of disturbances in the atmosphere is in general larger than for their decay. This is important while examining the stability of the gas-field system in the Galaxy.

It is very useful to study the global equilibrium states in order to compare with the observation and to understand the physical state of the gas-field system in the Galaxy. In this review I do not consider hydrostatic equilibrium studies carried out on self gravitating cloud of gas, but confine to the study of the tenuous interstellar medium which extends to the halo. Table 1 summarizes the important studies made in this area and in the following I discuss a few of them briefly. In the pioneering work, Parker(1966) first showed that the observed scale height of gas, the CR density and MF strength in the solar neighbourhood is roughly consistent with the expectation from the hydrostatic equilibrium. He made three assumptions, which are (a) the distributions of gas, MF and CR perpendicular to the galactic plane are similar, (b) the gravitational force acting on the gas is constant over one scale height, and (c) the gas is isothermal: ie the rms velocity u of the gas is independent of z. As a result, the derived gas distribution deviates from that observed beyond about 100 pc. Improvements have been made during the last two decades over this work. Instead of the assumption (b), Kellman (1972) made use of g(z) determined by Oort(1960), who made use of the observed velocity and density distribution of K giants. However, the results of Kellman were only marginally different from those of Parker and he was able show that the half thickness of gas in the outer parts of the Galaxy should increase.

The deviation of the calculated gas distribution from the observed was attributed (eg. Daniel and Stephens,1975; Thielheim,1975; Stephens,1979) to the result of assumption (a). The next major step was undertaken by Badhwar and Stephens (1977), who dropped all assumptions (a) to (c). They made use of the observed gas distribution, the galactic model (Schmidt, 1965) for g(z) and the two component model of the interstellar gas, to derive horizontal equilibrium states. The form of $\{P_T(z) - P_G(z)\}$ derived from Eqn.2 was found to be very different from $P_G(z)$. They calculated the radio emission in the halo by assuming that $P_{CR}(z) = P_{MF}(z)$ and the CR electron spectral shape at all z is the same as that near the solar vicinity. A comparison of the calculated the integral radio emission towards the galactic pole with the observed spectrum suggested the need for increasing $P_T(z)$ and hence a halo gas component was introduced to account for the radio observation. This halo component has a scale height H_h of a few kpc with a density of about 10^{-2} atom/cc at z = 0. A typical model is shown in Figure 1 for a condition that the clouds are not dynamically coupled to the system and a halo gas with H_h = 2 kpc. In this figure the behaviour of P_T, P_G and the radio emissivity at 400 MHz are shown as a function of z. The flattening noticed beyond 10 kpc is due to the inclusion of intergalactic gas with a constant density of 10^{-5} atom/cc.

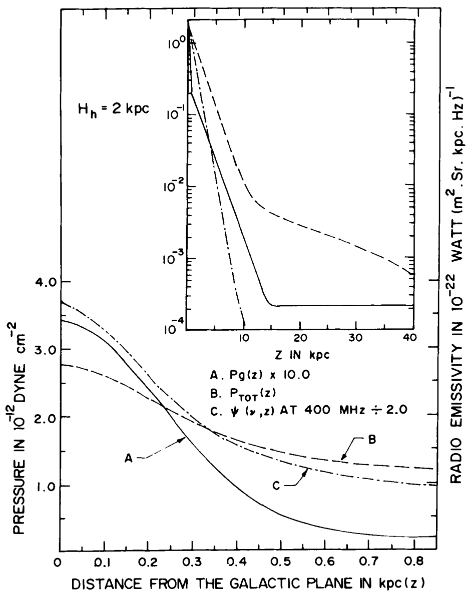

Fig.1 The distribution of P_G,P_T, and radio emissivity at 400 Mhz as a function of z for a horizontal equilibrium model with H_h = 2 kpc.

The above horizontal equilibrium model was able to satisfy all the available observations in a consistent manner at that time. Two important aspects came out of this study. (i) The need for the halo gas with a column density of about 10^{20} atom/cc. This value is found to be in agreement with the free electron density of (0.8 - 1.4)x10^{20} cm^{-2}, determined from dispersion measures from pulsars located in clusters 47 Tuc and M15 (Reynolds, 1989). (ii) It can be seen from Figure 1 that the distribution of radio emission is approximately exponential with a scale height about half that of the gas. It was clear then that a radio halo in the conventional sense of a volume with uniform radio emissivity cannot exist, but the halo can be identified up to a few kpc by a high resolution telescope with a dynamic range of at least 50. Indeed, the later observations of edge on galaxies showed that the intensity falls of rapidly with distance from the plane (eg. Sukumar and Velusamy, 1985). However, this model of Badhwar and Stephens was found to be stable only for > 1.0 (Lachieze-Rey et al, 1980).

An improvement was introduced by Ghosh and Ptuskin (1983) in this study by determining P_{CR} using diffusion model. They assumed that hot coronal gas and random MF to dominate in the halo and equipartition of energy densities to exist between them. However, they did not take into account the MF tension arising from random field orientation. Their major conclusion was that though P_{CR} and P_{MF} are not the same at all values of z, they are of the same magnitude. Because of the assumption that $P_G = P_{MF}$ in the halo, P_{CR} becomes smaller for larger values of halo gas temperature. The calculated radio emission does not show an exponential decrease with z.

TABLE 1.
Summary of the study carried out on the hydrostatic equilibrium of gas-field system in the Galaxy.

Author/s	Outcome of the study
Parker(1966)	Showed the consistency of derived P_G, P_{CR}, P_{MF} in the solar neighbourhood with the observation.
Kellman(1972)	Explained the observed increase of the thickness of gas disk in the outer parts of the Galaxy.
Badhwar and Stephens(1977)	Postulated halo gas with $N_G \sim 10^{20}$ / cm^2. Predicted extended distribution of CR & MF in the halo and derived (P_{MF} + P_{CR}) & radio emissivity, E_R, as a function of z. Predicted E_R to decrease exponentially with z.
Fuchs and Thielheim(1979)	Showed that gas clouds may not be coupled to the interstellar MF.
Ghosh and Ptuskin(1983)	Postulated the random MF pressure to be in equilibrium with the hot halo gas. Showed that $P_{MF} \sim P_{CR}$ and calculated P_{MF}, P_{CR} & E_R as a function of z.
Chevalier and Fransson(1984)	Demonstrated the possible support of coronal hot gas in the halo by CR.
Bloemen(1987)	Postulated the existence of hot halo gas & predicted its temperature profile. Derived the distribution of (P_{CR} + P_{MF}) in the halo and a condition relating the $H_{h,G}$ and $n_{h,min}(0)$.
Boulares and Cox(1990)	Invoked magnetic tension to support the system. Derived distributions of P_{MF}, P_{CR}, orientation of MF. Calculated the velocity dispersion profile of warm halo gas.

A detailed study was undertaken by Bloemen (1987), who introduced more recent information available on g(z) and on the gas distribution of atomic and molecular hydrogen. His analysis was motivated by the desire to obtain stable equilibrium states. He calculated $P_T(z)$ from Eqn.2 for various values of H_h and $n_h(0)$. Figure 2 shows the derived distribution of P_T for H_h = 6kpc. He also calculated the minimum gas pressure $P_{G,min}$ required to have stability by setting in Eqn.4, =0. and $_c$ = 1. These are also shown in the same figure as a set of curves starting from the same point in the plane. It is clear from this figure that, while $P_{G,min}$ is very much smaller than P_T at small values of z, it becomes equal to P_T beyond a few kpc. As a result , $\{P_T - P_{G,min}\}$, which is the pressure due to MF and CR decreases to 0 beyond a few kpc. Consequently, it is expected that the radio emission does not follow an exponential distribution in the halo.

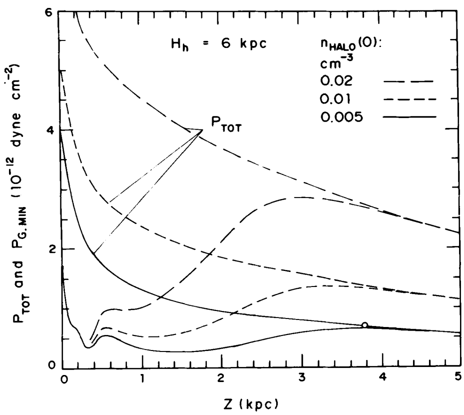

Fig.2 The distribution of P_T and $P_{G,min}$ as a function of z for various values of the halo gas density.

He set constraints from the integrated radio emission towards the pole at 30 MHz, by taking $\{P_{MF}(0) + P_{CR}(0)\}$ = 1.5 x 10^{-12} dyne / cm^2. From this he derived a relation $n_{h,min}(0)$ $(H_h$ / 1kpc$)^2$ = 0.17 cm^{-3} between the minimum halo gas density at z = 0 and the H_h. From this we find that H_h > 5kpc, in order to match the observed column density of free electrons. He also derived the temperature of halo gas as a function of z using the value of P_G for various halo gas distribution. These are shown in Figure 3. An interesting feature that one notices from this figure is that the gas temperature has a minimum value of about (2 - 3)x10^5K between 1 and 2 kpc, which is in agreement with the UV absorption line measurement from the halo. The temperature of the halo gas for H_h = 5 kpc is about 8x10^5K. It is clear that unless the radiative cooling of the halo gas is compensated by energy input from sources, equilibrium can not be maintained over a sufficiently long period of time. It may also be noted that the apparent behaviour of $\{P_{CR}+P_{MF}\}$ is forced upon by demanding minimum stability condition and setting $\{P_{CR}(0) + P_{MF}(0)\}$ = 1.5x10^{-12} dyne.cm^{-2}, which is uncertain by a factor 2. Cox (1990)

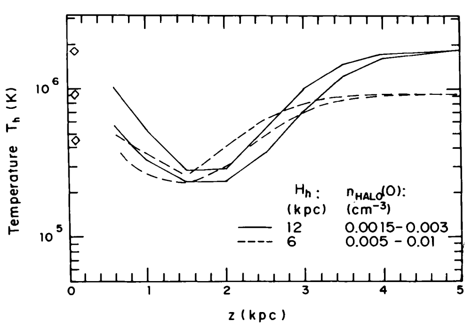

Fig.3 The temperature profile of the halo gas for different values of H_h and $n_h(0)$.

pointed out that the existence of hot coronal gas in the halo is not very well supported by the observations. Therefore, Boulares and Cox(1990) examined the equilibrium condition assuming a warm gas to exist in the halo, as in the case of Badhwar & Stephens. They invoked the MF tension resulting from the orientation of MF to provide support to the gas. They derived the distribution of variety of parameters in the halo as shown in Table 1.

It may be pointed out that in all the above discussions, the hydrostatic equilibrium is examined only in the solar neighbourhood. It has been brought to notice by de Boer (1990) that the situation is very different in the inner parts of the Galaxy, where it is difficult to provide support to the gas-field system in the halo. In the inner parts of the Galaxy, the gravitational field is much stronger and the gradient is also large. Solution to this problem lies in the study of nearby edge-on galaxies, where one can directly compare the expectations with the observations.

4. OBSERVATIONAL TESTS AND DISCUSSION

While some of the above deductions are only consistency checks for the validity of hydrostatic equilibrium, others are predictions which can be tested by observations. A detailed analysis of the radio profile of the edge-on galaxy NGC 4631 was carried out by Stephens and Velusamy (1990) at 1465 MHz. They examined the radio brightness as a function of z at different positions along the major axis. They found that, except near the plane, the distribution is exponential up to about 5 kpc. The radio scale height H_R varies from 1.25 to 2.5 kpc; the inner galaxy having smaller H_R. The true variation may be much larger as a function of R since the observations relate to the integrated emission along the line of sight. This appears to be consistent with the idea that variation of g(z) in the inner parts of the galaxy would result in a steeper gradient of P_T. Exponential distribution of E_R is also seen in NGC 891 (Hummel,1990). Thus, the radio emission in the halo seems to follow an exponential distribution. Stephens and Velusamy (1990) noticed a flattening of the radio profile from the exponential distribution in some regions of NGC 4631. This behaviour can be expected from the interaction of infalling gas with the halo gas, leading to possible turbulence and acceleration of CR.

Free electron distribution in the halo provides evidence to the existence of halo gas, because it is expected that the electrons constitutes the electron component of the ionized gas. Pulsar dispersion measures directly give the column density of free electrons. An analysis of the pulsar data shows (Reynolds,1990) that the column density of free electrons is $\sim 7\times10^{19}$ cm^{-2} and the observations can be fitted with a scale height $H_{h,e}$ of $\sim$ 900 pc. However, the UV absorption studies show that the distribution of high ions in the halo has a larger scale height of $\sim$ 3 kpc (Salvage, 1990). It is essential that a large sample of pulsar at high z is required to estimate the value of $H_{h,e}$ and to

https://doi.org/10.1017/S0074180900089257 Published online by Cambridge University Press

determine its dependence on R. It appears from these studies that the gas in the halo is predominately ionized.

At this stage one may compare the calculations with the observations. As an example, I have shown in Table 2 some of the predictions or postulates along with the observations. Though this table reflects the sad state of the available observational tests, it is clear that one can test the model predictions by making proper observations both in our Galaxy and in external galaxies. It may be noted that the value of $H_{h,G}$ is very important input parameter in the study of the hydrostatic equilibrium. The difference in the derived values from UV absorption lines and from pulsar dispersion measures is rather large. This difference may be considerably narrowed in the near future. It ia also clear that the external galaxies show that the radio distribution is exponential in the halo and thus sets very strong constraint on the hydrostatic equilibrium models.

TABLE 2.
Summary and observational test

Parameter	Badhwar & Stephens	Bloemen	Boulares & Cox	Observation
$P_{MF} + P_{CR}$ dyne/cm^2	$\sim 2.5\times10^{-12}$ (predicted)	$\sim 1.5\times10^{-12}$ (assumed)	$\sim(2-4)\times10^{-12}$ (assumed)	good within a factor of 2
$H_{h,G}$	~2 kpc (postulated)	~5 kpc (expected)	1.5 kpc (assumed)	0.9 kpc# ~3 kpc*
$H_{h,radio}$	$H_{h,G}/2.$	not exponential	not predicted	exponential
$T_{h,Gas}$	warm (assumed)	hot (variability predicted)	warm (dispersion predicted)	?

electrons; * high ions

It is clear that observation of edge-on galaxies in radio wave lengths with a high angular resolution and flux contrast at a level of about a 500 will provide in the future valuable information on the dynamics of the gas-field system. Continuum measurements furnish information on the halo structure and the spectral shape, while 21 cm observation provides valuable details on the neutral gas distribution. Using the next generation of high resolution X - ray telescopes, information can be obtained on the temperature and column density of halo gas as a function of distance from the plane. Future measurements of the gamma rays in the Galaxy at high latitudes would also furnish information on the gas distribution in the halo, which is mostly ionized. These are the optimistic expectations of the future. Theoretical breakthrough can be also made by including dynamical effects, such as the CR sources, radiative cooling and heating by sources and from hydrodynamic interactions, and the effect of small and large scale explosive phenomena in the study of the stability of the system.

REFERENCES

Badhwar, G.D., Stephens, S.A. (1977) Ap. J., 212, 494.
Bloemen, J.B.G.M. (1987) Ap. J., 322, 694.
Boulares, A., Cox, D.P. (1990) to appear in Ap. J.
Chevelier, R.A., Fransson, C. (1984) Ap. J., 279, L43.
Cox, D.P.(1990) this Symposium.
de Boer, H. (1990) this Symposium.
Daniel, R.R., Stephens, S.A. (1975) Sp. Sci. Rev., 17, 45.
Fuchs, B., Thielheim, K.O. (1979) Ap. J., 227, 801.
Ghosh, A., Ptuskin, V.S. (1983) Ap. Sp. Sci., 92, 37.
Hummel, E.(1990) this Symposium.
Lachieze-Rey, M., Asseo, E., Cesarsky, C., Pellat, R. (1980) Ap. J., 238, 175.
Kellman, S.A. (1972) Ap. J., 175, 353.
Mouschovias, T.Ch. (1974) Ap. J., 192, 37.
Mouschovias, T.Ch. (1975) Astr. Ap., 40, 191.
Oort, J.H. (1960) Bull. Astr. Inst. Neth., 15, 45.
Parker, E.N. (1966) Ap. J., 145, 811.
Parker, E.N. (1969) Sp. Sci. Rev., 9, 651.
Reynolds, R.J. (1989) Ap. J., 339, L29.
Reynolds, R.J. (1990) this Symposium.
Savage, B.D. (1990) this Symposium.
Shu, F.H. (1974) Astr. Ap., 33, 55.
Stephens, S.A. (1979) in 'Non-Solar Gamma Rays' eds. Cowsik, R., Wills, R.D., Pergamon Press, p.191.
Stephens, S.A., Velusamy, T. (1990) Proc. 21st Int. Cosmic Ray Conf., Adelaide, 3, 221.
Sukumar, S., Velusamy, T. (1985) MNRAS, 231, 367.
Thielheim, K.O.(1975) in 'Origin of Cosmic Rays' eds. Osborne, J.L, Wolfendale, A.W., Reidel, Dordrecht, p.165.
Zeweibel, E.G., Kulsrud, R.M. (1975) Ap. J., 201, 63.