MODELS OF THE INTERSTELLAR MEDIUM

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ABSTRACT

Up-to-date models of the interstellar medium should account for the existence of at least three phases of the interstellar gas, a hot phase at $\sim 10^6$ K (HICM), a warm phase at $\sim 10^4$ K (WICM) and a cold phase at $\lesssim 10^2$ K (clouds). Recent observations of interstellar absorption lines are used to derive information about the physical properties and the spatial distribution of these phases. Evidence based on observations of C^+ absorption lines indicates that the photoelectric threshold of interstellar dust grains is about 6 eV, much lower than previously thought. If the photoelectric threshold is indeed of this magnitude the WICM can easily be heated to temperatures in the range 6000 to 8000 K by photons of the general interstellar radiation field with $\lambda > 912$ Å. The analysis of interstellar CH^+ and O VI absorption lines suggests that these lines are formed in gas associated with clouds in regions of enhanced pressure that occupy about 10 percent of interstellar space (SN cavities). The CH^+ lines are formed in compressed WICM shells around clouds and the O VI lines in conductive interfaces between the WICM and the HICM. The velocity characteristics of the observed lines make shock waves a less probable source of the absorbing gases.

1. INTRODUCTION

Observations of far-ultraviolet absorption lines of O VI (at 1032 and 1038 Å) with the spectrometer on board the COPERNICUS satellite (Jenkins and Meloy 1974) and the detection of wide-spread soft X-ray (0.1 - 2 KeV) emission (Williamson, Sanders, Kraushaar, McGammon, Borken and Bunner 1974) have demonstrated the existence of a hot ($\sim 10^6$ K) very tenuous third phase of the interstellar gas, in addition to the previously known warm ($\sim 10^4$ K) and cold ($\lesssim 10^2$ K) phases. The discovery of this hot phase has revolutionized our picture of the interstellar medium. Cox and Smith (1974) showed that the observed SN rate is sufficiently large that SN remnants will overlap before they are destroyed by cooling and recombination. Thus an interconnecting tunnel system of

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 301–310.

hot gas is generated that regulates the large-scale dynamics of the interstellar gas. A comprehensive model of this 3-phase ISM was developed by McKee and Ostriker (1977). Led by the principle that all phases of the ISM must be roughly in pressure equilibrium they presented a picture where clouds are destroyed by evaporation in the hot gas due to thermal conduction (Cowie and McKee 1977; McKee and Cowie 1977) and are formed by condensation of cool gas swept-up by SN shocks. The clouds are surrounded by shells of warm gas (WICM) and embedded in hot gas (HICM).

In this paper I shall not attempt to review this rapidly developing field (excellent recent reviews by Tanaka and Bleeker (1977) and by McCray and Snow (1979) are available in the literature) but rather concentrate on several areas where the model of McKee and Ostriker can be improved and refined by making use of recent observations of interstellar absorption lines.

2. THERMAL BALANCE OF THE INTERSTELLAR GAS

In their model McKee and Ostriker assume that the largely neutral WICM (their component WNM) is heated and ionized by soft X-rays with energies of ∿ 60 eV which are thought to be produced in SN explosions. This assumption is highly uncertain because the observed soft X-rays with energies in the range 0.1 - 2 KeV fail by about two orders of magnitude to produce the heating rate of $\sim 4 \times 10^{-27}$ erg cm^{-3} s^{-1} required to keep interstellar gas with $n_H = 0.4$ cm^{-3} at temperatures of about 7000 K (cf. Tanaka and Bleeker 1977). It seems much more attractive to heat the WICM by photoelectrons ejected from dust grains by photons of the interstellar radiation field with wavelengths longward of the Lyman limit (Jura 1976; de Jong 1977). The flux of these photons is quite large and they virtually all end up being absorbed by dust grains. At low densities, typical for the WICM, the number of recombinations of electrons with dust grains is reduced and the grains become positively charged so that the effective photoelectric threshold is increased and the heating rate correspondingly decreased. Below some critical density cosmic ray heating takes over (cf. de Jong 1977).

Draine (1978) has correctly pointed out that in the earlier work of Jura and de Jong cooling of the gas by recombinations of electrons with dust grains (∿ 1 eV per recombination at WICM temperatures) was not included. Using parameters suggested by laboratory experiments of grainlike materials he concluded that the WICM could not be heated to temperatures of 6000 to 8000 K by photoelectrons from dust grains.

Recently Pottasch, Wesselius and van Duinen (1979) analyzing COPERNICUS observations of UV resonance lines of C^+, the main coolant of diffuse interstellar clouds, have derived cooling rates in eight interstellar clouds of $\sim 10^{-25}$ ergs cm^{-3} s^{-1} per Hydrogen nucleus, in excellent agreement with theoretical calculations of C^+ collisional excitation rates by H and H_2 impact at ∿ 100 K (Launay and Roueff 1977; Flower and Launay 1977). These observed high cooling rates can be balanced by photoelectric heating, the main heating mechanism in diffuse clouds, if one adopts the usual estimate of the photoelectric yield y = 0.1 (de Jong 1977; Draine 1978) and a photoelectric threshold

$v_d \simeq 6$ eV, much lower than previously thought. A lower value of v_d results in a larger heating rate because the number of photons that can "ionize" the grains increases and because the average energy of the photoelectron increases.

In order to investigate the thermal balance of the interstellar gas with the revised parameters I have redone my earlier calculations (de Jong 1977) with the following additions/modifications:

(i) the term $((1-x)/x)^2$ in the original expression of the heating rate is replaced by $((1-x)^2/x + x_k(1-1/x^2))$ to include the effect of recombination cooling (an error of a factor $1/x$ in the original expression is at the same time corrected),

(ii) the depletion of the coolants varies smoothly from ζ Oph depletion factors at low temperatures (clouds) to λ Sco depletion factors at high temperatures (WICM; cf. de Jong 1977).

The results of this calculation for various values of y are shown in figure 1. The gas is assumed to be ionized by cosmic rays with an ionization rate $\zeta = 10^{-16}$ s^{-1}, consistent with observed molecular abundances in diffuse interstellar clouds (Hartquist, Black and Dalgarno 1978). The importance of photoelectric heating of the WICM is obvious from a comparison of the cases with y = 0 (no photoelectric heating at all) and y = 1 (100% efficiency of the photoelectric effect). The effect of recombination cooling can be observed in the curve for y = 1 which

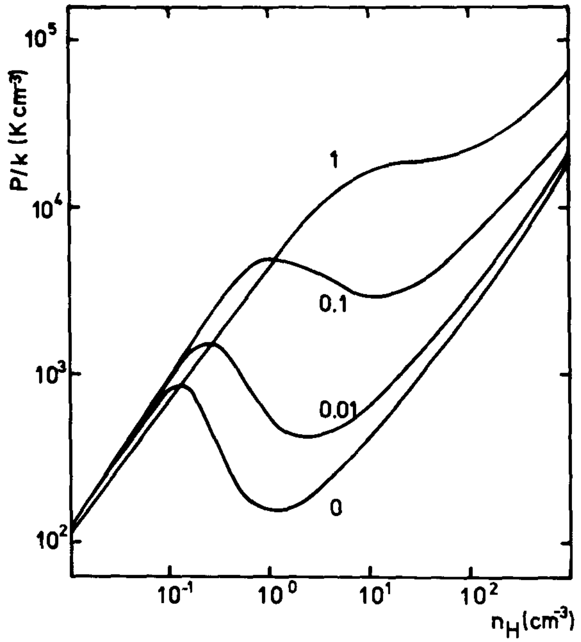

Figure 1. Equations of state of the interstellar gas for various values of the photoelectric yield of dust grain material. The other parameters adopted for this calculation are $v_d = 7$ eV, $\zeta = 10^{-16}$ s^{-1} and $\chi = 1$ (Habing's radiation field).

at high temperatures (low densities) falls below the other curves. Grain recombination cooling dominates over grain heating (negative grain heating) only for y = 1 and $n_H \lesssim 0.1$ cm^{-3}. Grain heating dominates over cosmic ray heating for $n_H \gtrsim 0.8$, 0.2 and 0.4 cm^{-3} for y = 0.01, 0.1 and 1, respectively. Probably the most realistic curve with y = 0.1 corresponds to cloud surfaces with $n_H \simeq 25$ cm^{-3} and T ≃ 120 K in pressure equilibrium at $P_0 = 3 \times 10^3$ k dyne cm^{-2} with a WICM with $n_H = 0.4$ cm^{-3} and T = 7100 K. This calculation confirms the earlier conclusion (de Jong 1977) that the WICM can be heated to temperatures in the range 4000 - 8000 K by photons of the general interstellar radiation field through the grain photoelectric effect.

In summary of this section I have collected in Table 1 several parameters of a 3-component ISM consistent with the thermal balance calculations above (n_H = Hydrogen density, n_e = electron density, T = temperature, r = (outer) radius and ϕ = volume filling factor). Every cloud is assumed to be surrounded by a WICM shell consistent with recent 21 cm observations by Dickey, Salpeter and Terzian (1979). For the sake of simplicity I have omitted the thin outer layer of the WICM shell that is fully ionized by photons with energies larger than 13.6 eV emitted by field B stars (cf. McKee and Ostriker 1977).

TABLE 1. Parameters adopted for a 3-component ISM

Component	n_H(cm^{-3})	n_e(cm^{-3})	T(K)	r(pc)	ϕ
HICM	0.0015	0.0015	10^6	-	0.80
WICM	0.4	0.014	7100	8	0.15
clouds	25	0.030	120	5	0.05

3. THE INTERPRETATION OF O VI AND CH$^+$ ABSORPTION LINES: SHOCKS OR COMPRESSED WICM SHELLS ?

In this section I shall attempt to analyze observations of interstellar O VI lines (λ1032 and λ1038) and of CH$^+$ lines (λ4232) assuming that the O VI lines are produced in an interface between the WICM and the HICM and that the CH$^+$ lines are formed in an interface between cold clouds and the WICM.

In Table 2 I have listed several parameters of O VI and CH$^+$ absorbing regions derived from statistical analvses of O VI lines in about 70 stars (Jenkins 1978 a,b) and of CH$^+$lines in about 30 stars (Hobbs 1973; de Jong 1979).

TABLE 2. Parameters derived from O VI and CH$^+$ observations

Species	<n>(cm^{-3})	N(cm^{-2})	ℓ^{-1}(kpc^{-1})	$\delta v_{\frac{1}{2}}$(km s^{-1})	T_{low}(K)
CH$^+$	2×10^{-9}	2×10^{12}	2	6	1000 K
O VI	2×10^{-8}	1×10^{13}	6	60	2×10^5 K

The quantity N represents the typical column density per absorbing element, $\langle n \rangle$ is the volume density per absorbing species averaged along the lines of sight towards all stars, ℓ^{-1} is the average number of absorbing regions along the line of sight, $\delta v_{\frac{1}{2}}$ is the r.m.s. full-width-at-half-maxium of the absorption lines and T_{low} is a lower limit to the temperature of the absorbing gas consistent with the smallest observed linewidths.

With the assumption that the absorption lines are formed in thin interfaces the volume filling factor of the absorbing regions equals by definition

$$\phi = \langle n_i \rangle \, \Delta r_i / N_i \tag{1}$$

while it may also be expressed as

$$\phi = p_i \phi_i \, \frac{3 \Delta r_i}{r_i} \tag{2}$$

where p_i is the fraction of clouds or WICM shells (component i) that have absorbing interfaces (with $\Delta r_i \ll r_i$, r_i and ϕ_i are the radii and the filling factors of component i (see Table 1) and $\langle n_i \rangle$ and N_i are the observed volume and column densities in the interface bordering component i (see Table 2). Inserting numerical values from Tables 1 and 2 I find

$$p_{cloud} \simeq p_{WICM} \simeq 0.1 \tag{3}$$

so that only about 10% of all clouds have CH^+ absorbing interfaces and about 10% of all WICM shells have O VI absorbing interfaces. The average number of absorbing elements along the line of sight equals (cf. eqs. (1) and (2))

$$\ell_i^{-1} = 2 p_i . 3 \phi_i / 4 \pi r_i^3 . \pi r_i^2 = \langle n_i \rangle / 2 N_i \tag{4}$$

where I have assumed that the line of sight intersects each interface twice. Inserting numerical values I find that there should be about three O VI absorbing elements per kpc and about one to two CH^+ absorbing elements per kpc, within the uncertainties in good agreement with the values in Table 2. From this simple analysis I conclude that the picture presented here is internally consistent and that the parameter ℓ^{-1} does not provide independent information about the distribution of the absorbing regions. It is tempting to interpret the fact that $p_{cloud} \simeq p_{WICM}$ as evidence that the same conditions that produce the O VI absorbing interfaces also lead to the formation of CH^+ absorbing interfaces.

In order to further analyse the O VI absorption lines I shall consider two alernative scenarios: (i) the O VI lines are produced by SN shock waves running into WICM shells, and (ii) the O VI lines are formed in conductive interfaces in regions of enhanced pressure in the ISM. Using the relation

$$\Delta r = N(\mathrm{O\ VI}) / x_O f_{O\ VI} n_H \tag{5}$$

and assuming a gas temperature of $T = 4 \times 10^5$K, a cosmic abundance of Oxygen $x_O = 6.8 \times 10^{-4}$ (depletion removed in hot gas) and $f_{O\ VI} = 0.1$ (Shapiro and Moore 1976) I have derived the parameters in Table 3. The

TABLE 3. Parameters characterizing O VI absorption regions

scenario	n_H(cm^{-3})	Δr(pc)	ϕ	ℓ^{-1}(kpc^{-1})
SN shock	1.6	0.03	1.8×10^{-4}	3.1
cond.int.	1.5×10^{-2}	3.2	1.9×10^{-2}	8.3

temperature of the O VI gas cannot be much lower than 4×10^5 K because otherwise the N V absorption lines would be much stronger than observed (York 1974).

The density of the shocked gas equals 4 times the pre-shock WICM density while the shock velocity required to heat the gas to 4×10^5 K is about 170 km s^{-1} (cf. Spitzer 1978). The thickness of the shocked gas layer with temperatures in the range $2 - 4\times10^5$ K and the resulting column density of O VI are in good agreement with the detailed shock calculations of Raymond (1979) scaled to a lower pre-shock density of $n_H =$ $= 0.4$ cm^{-3} (note that N(O VI) is independent of the pre-shock density). For shock velocities below about 150 km s^{-1} no observable amounts of O VI are produced in the post-shock gas. The model of McKee and Ostriker (1977) predicts that SN remnants with shock velocities $\gtrsim$ 150 km s^{-1} fill about 10% of space consistent with the result $p_{WICM} \simeq 0.10$ derived earlier.

However, a shock model fails to explain the observations in two respects. First, the calculations predict N V column densities about two orders of magnitude larger than observed (York 1974; Raymond 1979). Secondly, the observed half-width of the O VI lines due to random motions of the absorbing elements along the lines of sight (see Table 2) is significantly smaller than expected from O VI lines produced in SN shock fronts, even if one takes account of the reduction in the radial velocity of the shocked gas by 3/4 due to the jump condition across the shock front (e.g. Spitzer 1978) and of the reduction by a factor $2/\pi$ due to the averaging over all inclination angles of shocks along the line of sight.

The gas density adopted in Table 3 for the conductive interface corresponds to a gas pressure four times larger than the average interstellar pressure ($P_0 = 3\times10^3$ k dyne cm^{-2}). According to the model of McKee and Ostriker about 10% of interstellar space is occupied by SN cavities with such internal pressures consistent with our earlier result $p_{WICM} \simeq 0.10$. The thickness Δr of the layer over which temperatures in the range $2 - 6\times10^5$ K occur (see Table 2) is as expected for a classical conductive interface between a WICM shell and hot ambient gas at $T_h = 8\times10^5$K (cf. Cowie and McKee 1977). The ratio of the N V to O VI column densities in a classical conductive interface equals $f_{N\,V}\,x_N/f_{O\,VI}\,x_O \cdot (T_{N\,V}/T_{O\,VI})^{5.2}$ (cf. Cowie and McKee 1977). Inserting $T_{N\,V} = 2\times10^5$ K, $T_{O\,IV} = 4\times10^5$ K, $f_{N\,V}/f_{O\,IV} \simeq 1$ (Shapiro and Moore 1976) and cosmical abundances of Nitrogen and Oxygen I find $N(N\,V)/N(O\,IV) \simeq 3\times10^{-2}$ in excellent agreement with the observations (York 1974). The number of absorbing elements along the line of sight ℓ^{-1} in Table 3 has been calculated using the values of Δr in the Table rather than assuming $\Delta r \ll r_w$.

Thermal conduction causes the WICM shells to evaporate. At the position in a classical conductive interface where the O IV lines are formed the flow velocity equals $v_f \simeq 10$ km s^{-1} for the parameters considered here (cf. Cowie, Jenkins, Songaila and York 1979). The observed O VI linewidths are quite consistent with gas streaming away with about this velocity from several WICM shells along the line of sight. A comparison of the central velocities of the O VI lines and of the strongest Ca II and Na I lines observed towards the same star also suggests relative motions of clouds and the O IV gas of order 10 km s^{-1}.

Based on their model McKee and Ostriker predicted O VI column densities of $\sim 4 \times 10^{11} cm^{-2}$ per conductive interface and assuming that the line of sight intersects two interfaces per cloud they could roughly explain the observed average volume density of O VI. The analysis above of more recent and more extensive observational material suggests that large enough amounts of O VI to explain the observations are only produced in conductive interfaces of clouds situated in regions of enhanced pressure and that 10% of interstellar space is occupied by these high pressure regions.

In the analysis of the CH^+ absorption lines that follows I shall also consider two scenarios: (i) CH^+ is formed in shock-heated gas at the edges of interstellar clouds, and (ii) CH^+ is formed in compressed WICM shells around clouds in regions of enhanced pressure in the interstellar medium. The discussion is based on the assumption that CH^+ molecules are formed and destroyed by the reactions $C^+ + H_2 \rightleftarrows CH^+ + H$, resulting in an equilibrium abundance of CH^+ (de Jong 1979).

$$n(CH^+) = x_C\, n(H_2) \exp(-4660/T), \tag{6}$$

where x_C is the Carbon abundance and where it is assumed that Carbon is fully ionized. The CH^+ abundance is directly proportional to the abundance of H_2. From the observations we derive for the CH^+ regions

$$N(H_2) = N(CH^+) \exp(4660/T)\ /x_C \tag{7}.$$

Using a recent estimate of the photodestruction time of H_2 by de Jong, Dalgarno and Boland (1979)

$$t_d = 1.6 \times 10^{-3} X^{-1} (N(H_2)^{\frac{1}{2}} \text{ years} \tag{8}$$

where X is an intensity scale factor of the interstellar radiation field and equating formation and destruction times one obtains for the molecular fraction of the Hydrogen gas (in the limit that $f_2 << 1$)

$$f_2 = 3.0 \times 10^{-13}\ T^{\frac{1}{2}} n_H\ X^{-1}\ (N(H_2))^{\frac{1}{2}} \tag{9}$$

In the derivation of eq.(9) it has been assumed that the sticking coefficient of H atoms on dust grains is independent of the gas temperature. In Table 4 I have listed several parameters of the CH^+ absorbing regions calculated using equations (4), (7) and (9). For all calculations a gas temperature of 4000K and Habing's radiation field (X = 1) has been assumed.

TABLE 4. Parameters characterizing CH^+ absorption regions

scenario	$n_H(cm^{-3})$	$N(H_2)(cm^{-2})$	f_2	Δr(pc)	ϕ	ℓ^{-1}
shock	100	8.7×10^{16}	0.025	0.022	7×10^{-5}	1.6
compr.shell	3	3.8×10^{16}	0.0051	1.6	5×10^{-3}	2.7

The pre-shock gas parameters at the cloud boundary are $n_H = 25cm^{-3}$ and T = 120K (cf. Table 1). A ζ Oph abundance of Carbon $x_C = 1.7 \times 10^{-4}$ has been adopted for the pre-shock gas. Since the time to reach H_2 equilibrium (eq.(8)) is much larger than the cooling time of the gas due to H_2 rotational excitation

$$t_c = 1770\ n_H^{0.27}/n(H_2) \text{ years} \qquad (10)$$

(fitted to the results of Elitzur and Watson (1978b) at 4000K) the pre-shock parameters must be used to obtain the H_2 abundance in the shocked gas. Dalgarno and Roberge (1979) have shown that H_2 is not destroyed in shocks with velocities of order 10 kms^{-1} considered here. Chemical equilibrium of CH^+ is reached "instantaneously" ($t_{CH^+} \simeq 50$ yrs). The derived thickness of the CH^+ layer is consistent with the cooling time for a shock velocity of about 5 kms^{-1}. To heat the gas to a temperature of 4000K a shock velocity of about 12 kms^{-1} is required. This shock could be due to a SN explosion but much decreased in speed by momentum losses in the WICM shell. The main point agsinst shocks as an explanation of the interstellar CH^+ lines is the fact that in most stars the observed CH^+ lines are centered at about the same velocity as the Na I and Ca II lines which are formed in the clouds (Hobbs 1973). In ζ Oph and one or two other stars where a clear velocity separation between the cloud gas and the CH^+ gas has been observed a shock explanation is attractive (Elitzur and Watson 1978a; Crutcher 1979).

The gas density and temperature adopted for the compressed WICM shell corresponds to a pressure of the gas four times larger than in the general interstellar medium. The assumed Carbon abundance $x_C = 7.4 \times 10^{-5}$ applies to a typical intercloud region (λ Sco depletion). H_2 equilibrium can not be reached in the compressed WICM shell within the time available before the gas cools. The value of the molecular Hydrogen fraction f_2 in Table 4 has been calculated with eqs.(8) and (10) from the condition t_{H_2} $(=t_d)=t_c(\simeq 3 \times 10^5$yrs).

If the observed CH^+ is indeed formed in warm compressed shells surrounding interstellar clouds one would expect velocity differences between the CH^+ and the Na I and Ca II lines not larger than a few kilometers per second (a fraction of the sound velocity c) in agreement with the observations. The time required to compress the WICM shell to a thickness of about 1pc (cf. Table 4) is about 10^5years ($\sim\Delta r/c$), of the same order of magnitude as the H_2 equilibrium and cooling time-scales. If mass is conserved during compression (evaporation negligible) the density in the compressed shell and its size are consistent with the values of the WICM parameters before compression in Table 1 (Δr = 3pc, $n_H = 0.4cm^{-3}$). While the WICM shell cools down after compression it probably merges with the underlying cloud because a stable WICM does not exist at a pressure of $4P_0$ (see fig.1, curve for y = 0.1). The ambient pressure relaxes back to average interstellar values (P_0) in a time of order 10^6yrs (cf. McKee and Ostriker 1977). As discussed before for the O VI lines the fact that only 10% of the WICM shells give rise to observable CH^+ lines is consistent with the predicted fraction of space occupied by SN cavities with internal pressures about four times larger than the average interstellar pressure.

If indeed both the CH^+ and the O VI lines are associated with the same WICM shells one would expect that the fraction of stars with O VI absorption lines that also show CH^+ absorption lines is larger than 1/5, the fraction of all stars that show CH^+ absorption lines (Adams 1949).

4. CONCLUSIONS

Recent (ultraviolet) absorption line observations have significantly increased our knowledge of the interstellar medium. As usual, with the increase in our understanding the problems become more complex but at the same time more interesting. I would like to stress the importance of future statistical studies of interstellar absorption lines. In spite of its limited wavelength resolution the International Ultraviolet Explorer has the capability to observe bright stars out to several kpc so that a large sample of local space can be investigated. At the present time the largest body of information of interstellar absorption lines in a statistical sense is still based on Adams (1949) thirty years old spectral survey of about 300 OB stars in the solar neighbourhood.

In preparing this paper I have profited from discussions and correspondence with D.P.Cox, B.T.Draine, D.J.Hollenbach and E.B.Jenkins.

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DISCUSSION:

P.A. Aannestad: If, as Dr. Jura pointed out, much grain growth takes place within the diffuse clouds themselves, the gas must heat up as the cooling elements deplete onto the grains. How does such a thermal evolution fit into the picture of thermal phases that you presented?

T. de Jong: If the depletion time is significantly shorter than the lifetime of clouds the thermal evolution of the clouds will be quite similar to that described several years ago by Meszaros in spite of the fact that in his calculations the clouds were heated by cosmic rays, I believe, rather than by photoelectrons from dust grains.

D. Cox: 1) The compressional work done on clouds after the passage of supernova shockwaves seems to be similar to what you need to overcome the cooling in your clouds.

2) McKee and Ostriker have successfully shown that thermal evaporation is so extreme that, in my opinion, it guarantees that surviving clouds will have magnetic fields parallel to their surfaces much as a pack of wolves guarantees that the members of a buffalo herd will all be healthy enough to withstand attacks from wolves.

T. de Jong: In response to your second comment I think that your American fable sounds quite suggestive.