

Martian Atmosphere: The Mariner Occultation Experiment

During the 1965 fly-by, Mars' upper ionosphere appeared surprisingly underdeveloped compared with Earth's.

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In the Mariner IV occultation experiment (1), the phase shifts of the telemetry carrier-wave were measured on Earth as the spacecraft passed behind the Martian atmosphere. The phase shifts may be interpreted to yield information about densities and density gradients for the neutral atmosphere at low altitudes and, at high altitudes, similar information about ambient ionization.

The derived surface pressure is in the range of 4 to 7 millibars, being almost independent of the composition. This value is slightly smaller than that found in several spectroscopic investigations during the 1965 Martian opposition (2). The ionospheric measurements show a maximum electron density, in late afternoon, of 9×10^4 electrons per cubic centimeter at a height of 120 to 125 kilometers and an electron scale-height of 20 to 25 kilometers.

This small scale-height and the low altitude of the ionospheric peak each suggested that the ionosphere is cooler than had been expected. Specifically, we (3) had computed models of the Martian thermosphere, for various amounts of CO and O (dissociation products of CO₂), and we had found temperatures well in excess of those that have been inferred (1, 4) from the

new observations. The highest concentration of CO (which acts as a thermostat by radiating with rotational transitions) that we assumed in the published models was 20 percent, but increasing the CO content cannot alone change the models enough to satisfy the observations. Far more important than the apparent discrepancy in temperature itself is the fact that ionospheres computed for these models would be drastically different from the one observed.

In this article we argue that CO₂ is not strongly dissociated, as we earlier assumed, and that the main ionospheric peak is analogous to the terrestrial *E* or perhaps *F1* region.

A completely different and rather ingenious interpretation has recently been proposed by Johnson (4). His entire model is based on the fundamental and reasonable postulates that the ionospheric peak is of the *F2* type and is composed of O⁺ ions. By "*F2* type," we refer to a high-altitude ionospheric region that is optically thin in the ionizing frequencies and in which the recombination rate increases downward more steeply than the O density; the daytime ionization density thus increases upward until the electron-ion gas can be removed readily by diffusion. Hence the ionization peak is formed at the height where the rates of diffusive and chemical removal of elec-

trons are comparable. Once the "*F2* postulate" is granted, the Mariner observations require a certain temperature and density structure, within rather narrow limits, of virtually the entire atmosphere. Our objections to this model are twofold:

First, for the low densities required in the *F2* region, it would be necessary for the temperature in the middle atmosphere to follow the vapor-pressure curve for dry ice, whereas on physical grounds it appears likely that the middle atmosphere would be in radiative equilibrium at temperatures well above the dry-ice values (5).

Second, Johnson's model requires a nearly isothermal ionosphere, which he tentatively ascribes to the strong radiative losses of heat in the CO₂ vibrational bands at 15 microns. However, our calculations show that, although CO₂ serves as an effective thermostat in keeping the temperature fairly low by terrestrial standards, a true thermosphere (where temperature increases with height) is nevertheless maintained by the deposition of solar ionizing and dissociating radiation and the conductive flow of heat downward.

Therefore we have sought a consistent picture of the Martian atmosphere that does not have these objections. A proper discussion of the structure of an atmosphere in which various processes are competing requires an elaborate analysis to weigh the relative importance of radiative exchange and conductive heating and the relative importance of turbulent mixing and diffusive separation. We have such a study underway, but for present purposes we regard each region of the atmosphere in a somewhat oversimplified way.

Photodissociation and Mixing

Before discussing the temperature structure, however, we must mention briefly the matter of photodissociation of CO₂. First let us consider the situation of local photochemical equilibrium. As CO₂ is dissociated into CO and O, the resultant O atoms may reassociate into O₂. Indeed, since O₂ is more read-

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ily formed by three-body association than is CO_2 and since its continuous absorption is stronger, O_2 becomes the main source of opacity in the wavelength region short of 1750 angstroms and helps shield the CO_2 from further dissociation (6). Hence the equilibrium abundances of O_2 and CO_2 are strongly coupled to one another. The two equations for photodissociation and three-body association of O_2 and CO_2 have been programmed for a computer, with the simple auxiliary conditions that the fractional compositions of carbon and oxygen are constant with height (7). The results of one such calculation are shown in Fig. 1.

The point here is that the lifetime of a CO_2 molecule against photodissociation is 3×10^6 seconds, or about 1 month, high in the atmosphere. But in the main dissociation region the lifetime is much longer. For example, with photochemical equilibrium, as illustrated in Fig. 1, the optical thickness to ultraviolet is 9.4 at the O_2 peak, so that here a CO_2 molecule could survive intact for 10^3 years.

It seems reasonable, therefore, to expect that mixing will greatly alter the distribution of gases, with appreciable amounts of CO_2 extending to great heights. In the remainder of this paper we consider the constituent gases to be homogeneously mixed throughout the atmosphere. This model is admittedly an oversimplification and in a sense lies at the opposite extreme from the ones based on complete dissociation (3).

Radiation Losses

For the lower and middle atmosphere we adopt an available radiative model (5) with a surface pressure of 10 millibars and with 44 percent CO_2 and the remainder N_2 (except for 0.4 percent O_2). This temperature structure should be approximately valid at least to the height where the radiative lifetime ($1/A = 0.37$ second, where A is the transition probability) becomes less than the lifetime for collisional deactivation ($1/\eta N_t$, where N_t is the total density and η is the rate coefficient for vibrational deactivation). We adopt the formula (8)

$$\eta = 1.9 \times 10^{-9} \exp(-82.8 T^{-1/2}) \quad (1)$$

cubic centimeters per second. This height is the *level of vibrational relaxation* (9) and occurs, in the adopted model, at 50 kilometers.

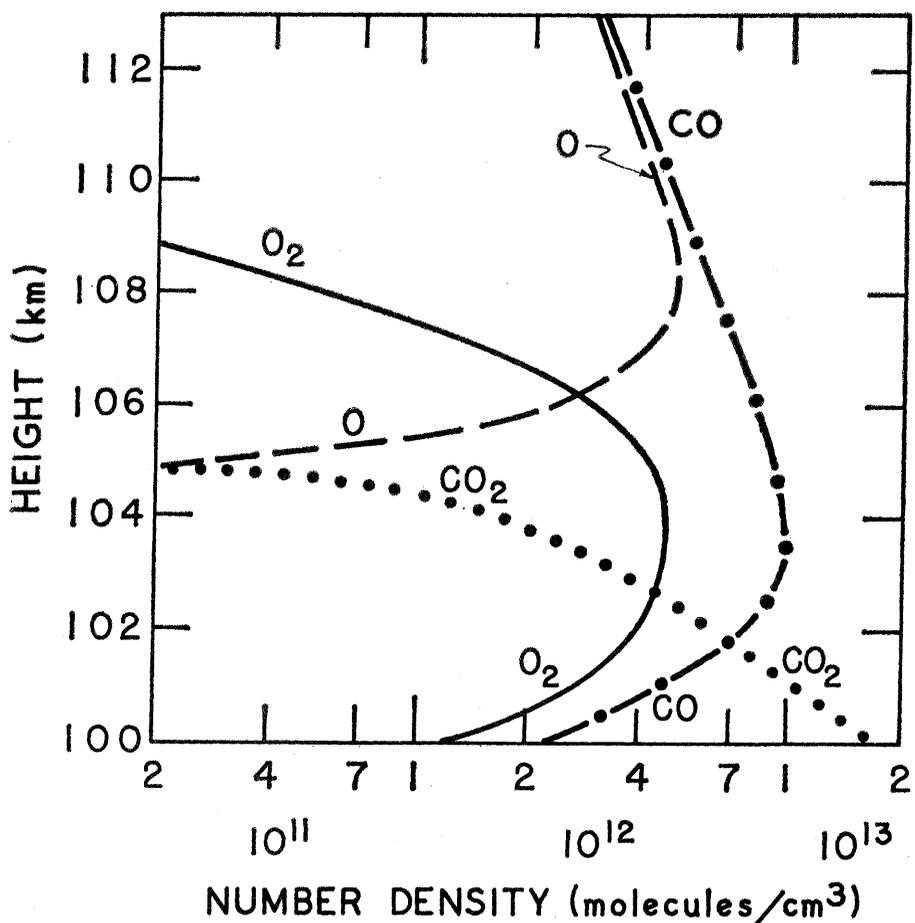


Fig. 1. Illustrative distribution of O_2 , O , CO_2 , and CO for photochemical equilibrium under the assumed conditions stated (see 7). The height scale has been selected to be in approximate agreement with the total densities of the model shown in Fig. 2.

Above this height it appears likely that radiative interchange loses its control over the temperature. The local energy balance here includes heat deposited or removed by conduction, heating by solar ionization and dissociation, and cooling by infrared radiation loss (10). Inclusion of the first two items in the heat-budget equation is relatively straightforward. We divide the problem of accounting for radiative losses into two parts. First we find the height below which radiative loss may be ignored for any one emission line. Then we estimate the total heat lost from a specified height due to the entire set of CO_2 lines that can contribute to radiative cooling.

Let us consider a single rotational line (with upper level j' and lower level j) in the CO_2 vibration-rotation spectrum. It has a mean cross section for absorption, $\alpha_{jj'}$, and a mean vertical optical thickness,

$$\tau_{jj'} = N_j(\text{CO}_2) H(\text{CO}_2) \alpha_{jj'}$$

where H is the scale height. The local albedo is $\bar{\omega} = A/(A + N_t \eta)$, with $A = \sum_j A_{jj'}$ being the total transition prob-

ability to all lower rotational levels and N_t the total gas density. One may find the radiational field at all depths from the equation of radiative transfer for an atmosphere that scatters, absorbs, and emits (from thermal excitation) radiation in a CO_2 line. With suitable boundary conditions this equation may be solved in the so-called "first approximation" by standard techniques (11). The solution strictly applies only to a homogeneous atmosphere (wherein $\bar{\omega}$ remains constant with depth), but it does illustrate the manner in which the radiation field changes with depth (12). At large $\tau_{jj'}$ but well above the level of vibrational relaxation (that is, in the region where $\bar{\omega} \approx 1$), the fraction of emitted thermal radiation that eventually escapes from the top of the atmosphere is of the order of $\exp(-K\tau_{jj'})$, where $K = [3(1 - \bar{\omega})]^{1/2}$. Thus the escaping flux is strongly diminished by the exponential unless

$$\tau_{jj'} \approx 1/K = [3(1 - \bar{\omega})]^{-1/2}$$

The physical reason for this relationship is clear. The number of scatterings required for a photon to exit from

depth τ by a random walk in space is of order τ^2 . At each scattering the photon has a probability of $1 - \bar{\omega}$ of being absorbed; hence the probability that a photon will escape is good only if $\tau^2(1 - \bar{\omega}) \approx 1$.

In a similar manner a photon may exit by a random walk in frequency within the line profile, if the molecules have frequent elastic collisions during the radiative lifetime. Thus eventually a quantum will acquire a Doppler-displaced frequency so far from the center of the line that the atmosphere becomes effectively transparent. With this mechanism the probability of a photon's escaping is essentially the fractional area of the profile for which $\tau < 1$. (For the CO_2 lines, Doppler broadening dominates the profile out to the frequency shift at which $\tau \sim 1$ for total densities less than about 10^{14} cm^{-3} , which covers the important radiating region.) When the probability of escape is small, its reciprocal is the mean number of scatterings required to escape. With the simple argument given above, it may readily be shown that this number is the order of $\tau_0(\pi \ln \tau_0)^{1/2}$, where τ_0 ($\approx 2\tau_{jj}$) is the optical thickness in the line center (13). Thus radiation can always escape more effectively by a random walk in frequency than by one in space, if there is redistribution of the Doppler profile at every scattering. Writing $\ln(2\tau_{jj}) \approx 5$, we obtain a criterion for radiative escape of

$$\tau_{jj} \leq [8(1 - \bar{\omega})]^{-1}.$$

The rate of thermal emission in a single line per cubic centimeter may be written, to close approximation (3), as

$$N_j(\text{CO}_2) A_{j'j} h\nu(1 - \bar{\omega}) \exp(-h\nu/kT).$$

Goody (14) gives a distribution function of $N_j \alpha_{jj'}$ for the various CO_2 lines, including those of minor isotopes, in the 15-micron region. Ignoring the "hot bands," we have weighted the above expression for the thermal emission of a line with this distribution function and integrated from the weakest lines to those with $N_j \alpha_{jj'} = 1/8H(1 - \bar{\omega})$ to find the amount of thermally emitted radiation that ultimately escapes from the atmosphere (instead of being reabsorbed as heat). We find a heat loss, per cubic centimeter per second, of

$$R_{\text{vib}}(z) = N_t N(\text{CO}_2) \eta h\nu e^{-h\nu/kT} \times [1 - (1 + \chi)e^{-\chi}], \quad (2)$$

where

$$\chi = \frac{1 \times 10^9}{N(\text{CO}_2)} \left(1 + \frac{A}{N_t \eta} \right). \quad (3)$$

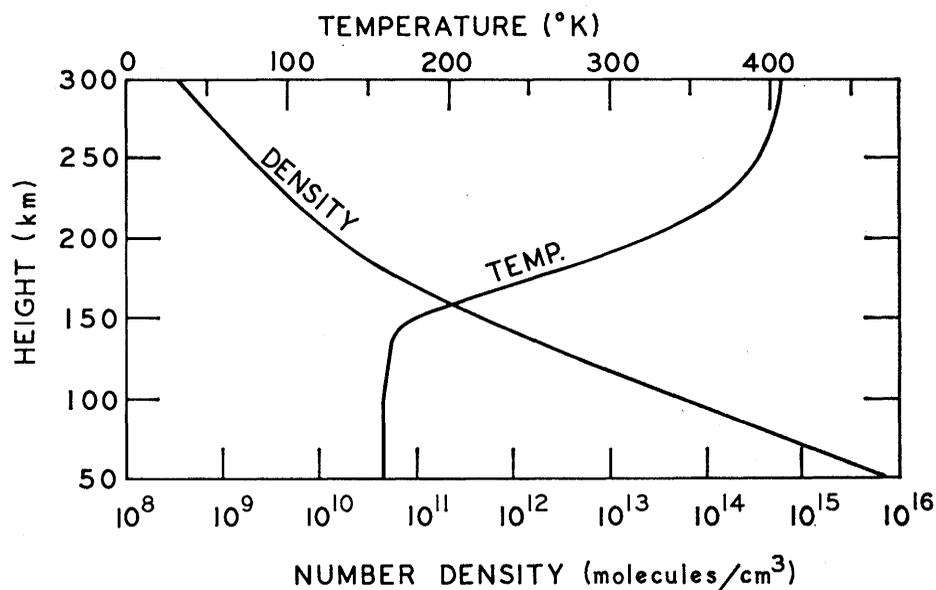


Fig. 2. Model upper atmosphere of Mars for negligible CO_2 dissociation and strong mixing. The exospheric temperature, T_x , is 410°K .

Because of the condition that collisions must be frequent within the radiative lifetime, this value of χ is strictly valid only for $N_t \approx 10^{10} \text{ cm}^{-3}$, but at this and lower densities there is effectively no blanketing of radiation. The terms in square brackets in Eq. 2 may be regarded as the blanketing correction to the radiation term for vibrational excitation; for small densities it is unity and for large densities, zero.

Rotational transitions from CO have such a long radiative lifetime that even at densities of 10^7 cm^{-3} the rotational levels are collisionally redistributed before reemission can occur; that is, $\bar{\omega} \approx 0$ everywhere. Thus the criterion of counting radiative losses only for $K_\tau \approx 1$ effectively substantiates our earlier proposal (3) that the CO rotational transitions will contribute to atmospheric cooling only for $\tau \approx 1$.

Model of Thermosphere

With radiative losses treated in the manner just described, we have computed the thermospheric model shown in Fig. 2. In addition, a number of other models were run to see how sensitive the model is to certain conditions: If cooling were accomplished mainly by a spatial random walk of photons (as described earlier), the temperature profile would be rather different in the lower ionosphere, but the exospheric temperature, T_x , would be about the same. With moderate or even substantial amounts of CO_2 dissociation and with diffusive separation, T_x is not

changed drastically, but of course the composition and densities are seriously affected at high altitudes. If the temperature at the base of the ionosphere is lower than the 160°K we have adopted, radiative loss at low altitudes is diminished and T_x will still build up to the order of 400°K . As an example, we ran a model with diffusive separation, starting with Johnson's (4) temperature (100°K) and densities at 70 kilometers. (This is the height Johnson suggests for the onset of diffusive separation and it is also the level at which direct solar heating begins to be important.) In this model the temperature at 125 kilometers (near the observed ionospheric peak) is 285°K and T_x is 375°K , both of which deviate seriously from the 85°K suggested by Johnson.

An interesting effect would occur if the temperature at the base of the ionosphere were appreciably greater than 160°K . In this case radiative cooling near the 150-kilometer level and above would more than exhaust the available solar energy flux, even for an isothermal atmosphere. Hence the temperature would initially decrease with height, and there would be a conductive flow of heat upward from the middle atmosphere. At higher altitudes the temperature gradient would become positive, developing a normal thermosphere. The fact that the temperature is so nearly isothermal at 100 kilometers in Fig. 2 is a consequence of this model's being close to the situation requiring a shallow minimum in the T profile.

The ionospheric peak observed by Mariner IV near 125 kilometers occurs at total densities around $5 \times 10^{12} \text{ cm}^{-3}$. We interpret this ionosphere as a Chapman-type *E* region, which peaks where the slant optical thickness is unity in the ionizing frequencies. For the sun at 70° zenith angle, the mean absorption cross section must be of the order of 10^{-19} cm^2 , which is suggestive of the x-ray region of the spectrum. The effective x-ray flux at the peak is likely to be some 5×10^8 photons per square centimeter per second. If the peak electron density is 10^5 electrons per cubic centimeter, the effective recombination coefficient is $2.5 \times 10^{-8} \text{ cm}^3/\text{sec}$. This is a reasonable ionospheric coefficient when dissociative recombination of a molecular ion is the rate-limiting process; a similar value applies to the terrestrial *E* region (15). Although x-rays would ionize all constituents in the region, reactions involving charge transfer or ion-atom interchange would be likely to deposit most of the ambient ionization in the form of NO^+ or perhaps O_2^+ , the molecules having the lowest ionization potentials of those species likely to be present in important amounts. Specifically CO_2^+ , even with a rate coefficient for dissociative recombination as high as $10^{-6} \text{ cm}^3/\text{sec}$ is likely to be removed by reactions with O_2 or O . With only modest dissociation of CO_2 and small-to-moderate rate coefficients, such reactions would still be the chief source for removal of CO_2^+ in the *E* region.

The Mariner observations (1) indicated an electron scale height (with base e) above the peak of 20 to 25 kilometers. For an idealized Chapman layer, the atmospheric scale height is $\Delta z/(2)^{1/2}$, where Δz is the height above the peak at which the electron density falls to one-half the peak value. Thus the observations suggest $H \approx 10$ to 12 kilometers, whereas the value in our model is 10.4 kilometers.

At somewhat higher altitudes, where the total density is of the order of 10^{10} cm^{-3} , one would expect to find ionization produced by solar ultraviolet radiation. For this *FI* region to be considerably less pronounced than the *E* region, three conditions must be satisfied: (i) With an incident ionizing flux of about 10^{10} photons per square centimeter per second, an effective recombination coefficient, $\alpha(\text{CO}_2^+)$, of at least $10^{-6} \text{ cm}^3/\text{sec}$ is required. Such a large value might apply to dissociative recombination of CO_2^+ . (ii) There

must not be a rapid reaction transforming this CO_2^+ into another ion that has a slower recombination rate; there is no reason at this time to expect that at *F*-region densities a sufficiently rapid reaction exists. (iii) The abundance of O and of O_2 must be low enough that O_2^+ does not become the dominant ion. [Reactions of O^+ with CO_2 to form $\text{CO} + \text{O}_2^+$ will rapidly remove O^+ ions with a rate coefficient of $k(\text{O}^+) = 1.2 \times 10^{-9} \text{ cm}^3/\text{sec}$ (16).] It appears that, to satisfy the latter condition, the O/CO_2 and O_2/CO_2 abundance ratios must each be less than about 10 percent, which requires that there be little CO_2 dissociation above 100 kilometers and little diffusive separation at the *FI* altitude (about 190 km).

With such a small amount of dissociation, there will be no Martian analog to Earth's *F2* region. For there to be an *F2*-type increase of ionization with height, O^+ would have to become the dominant ion below the height where ambipolar diffusion becomes the main process removing ions. With the large rate coefficients, $k(\text{O}^+)$ and $\alpha(\text{CO}_2^+)$, quoted above and the small O/CO_2 ratio required to explain the absence of a detectable *FI* region, it does not seem likely that O^+ can obtain this dominance.

The above ionospheric model is based on a specific chemical composition (44 percent CO_2 , 56 percent N_2) and the model can vary with composition. T. M. Donahue (17) has noted that in the extreme case of a pure CO_2 atmosphere, the observed ionospheric peak might occur at total densities the order of 10^{11} molecules per cubic centimeter. Low gas densities at 125 kilometers would also be implied by any composition having a large mean molecular weight, such as a carbon dioxide and argon mixture. In this situation, which cannot be definitely excluded, the peak might arise mainly from solar ultraviolet radiation rather than from x-rays. Then the lower electron density in the x-ray *E* region would imply a larger effective recombination coefficient than the value suggested above. But the main features of the thermal structure of the atmosphere, including a moderately high exospheric temperature, should not be significantly altered.

Gross, McGovern, and Rasool (18) have recently computed Martian temperatures for CO_2 completely dissociated in the thermosphere. They obtain exospheric temperatures of $550^\circ \pm$

150°K ; these values are somewhat lower than those in our previous models (3), which were computed in the same way. It appears, therefore, that they simply used a lower heating efficiency than did we in our earlier work, although they do not state their adopted parameters. In any event, the model calculations of Gross, McGovern, and Rasool still lead to inconsistencies between the computed and observed ionospheres: They have interpreted the Mariner observations in terms of O^+ ions with a diffusion theory, implying that the ionosphere is an *F2* region, whereas in their model the *F2* ionization would be formed well above 125 kilometers. It seems to us that this internal inconsistency invalidates most of their discussion.

Summary

Observations of the Martian ionosphere with the Mariner IV spacecraft have indicated that the upper atmosphere of that planet differs widely from models we proposed earlier. Those models were based on the assumption that there is complete photodissociation of CO_2 in the thermosphere, but they were otherwise the result of a straightforward application of the heat-budget equation. F. S. Johnson has recently proposed a radically different semiempirical model, which is based on the assumptions that the ionosphere peak is, as on Earth, of the *F2* type and that O^+ is the dominant ion. There is no true thermosphere in this model, for the temperature of the entire upper atmosphere would have to remain below 100°K to fit the observations. We have taken issue with Johnson's proposal on the grounds that his temperature profile could not be maintained. We have computed a model atmosphere, with 44 percent CO_2 and 56 percent N_2 , that will fit the observations, provided that CO_2 is not strongly dissociated. The major ionization is in an *E* region produced by solar x-rays; the dominant ion is probably NO^+ or O_2^+ . A physical discussion of the radiative losses by CO_2 shows that a normal thermosphere develops and that the exosphere temperature (at the top of the thermosphere) is at least 400°K . Absence of strong ionization peaks corresponding to the terrestrial *FI* and *F2* regions is plausible. If the mean molecular weight is considerably larger than that assumed in this model, the

observed ionospheric peak might be an *F1* region produced by solar ultraviolet radiation. It is still plausible in this case that no *F2* peak will develop, and the thermal structure is not likely to differ importantly from that shown in Fig. 2 (18).

References and Notes

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10. There is still some radiative exchange above the height of vibrational relaxation, but we have not been able to find a simple criterion to show rigorously at what point conduction takes over the dominant role from radiation in establishing the temperature. In practice it makes little difference to these models, as the conductive flux and resulting temperature gradient are very small between 50 and 100 km; in this region radiative equilibrium would also produce a nearly isothermal atmosphere.
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16. E. E. Ferguson, private communication.
17. T. M. Donahue, private communication.
18. S. H. Gross, W. E. McGovern, S. I. Rasool, *Science* **151**, 1221 (1966).
19. This article is contribution No. 148 of the Kitt Peak National Observatory. The observatory is operated by the Association of Universities for Research in Astronomy, Inc., under contract with NSF. We are indebted to D. M. Hunten, R. M. Goody, and T. M. Donahue for many helpful discussions during the course of this work.

Inductive Processes in Embryonic Development

Most organs form as a result of gradual cumulative effects of interactions among embryonic tissues.

A. G. Jacobson

During development the cells of a multicellular organism become different from one another although they are presumably endowed with identical genomes. The mechanisms of cell differentiation present some of the most provocative problems of modern biology. In many animal embryos one such

mechanism is embryonic induction. In general terms, embryonic induction is an interaction between one tissue (the inductor) and another responding tissue as a result of which the responding tissue takes a course of differentiation it would not have followed had the interaction not occurred.

It would be well if we knew when, or even if, induction begins and ends, as it is very difficult to untangle induction processes from other processes that occur before and after them or concurrently with them. Embryonic induction is part of a continuum of developmental processes. But the concept of induction, once separated out and named, has suffered reification. A number of papers imply or refer to "the moment of induction," and attention has prematurely shifted from study of the *process* of embryonic induction to a search for "the inductor substance." Induction has been studied for more than 60 years, but only recently have any inductive tissue systems been reasonably well defined with respect to their timing and spatial arrangements. The purpose of this discussion is to describe some of these inductive systems.

Programming for developmental events begins as early as oögenesis (1),

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