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BEHAVIOR OF MATTER IN SPACE*

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I. INTRODUCTION

Study of the stars is one of man's oldest intellectual activities. Study of the matter between stars is one of the youngest. Even as recently as some thirty years ago, the existence of interstellar material was uncertain. In 1920, for example, a prominent astrophysicist, in an extensive discussion of the calcium absorption lines, now believed to be truly interstellar, concluded: "Hartmann's suggestion that the [calcium] clouds lie between the observer and the star . . . cannot be accepted. The hypothesis that the calcium cloud is a part of the star's atmosphere seems most satisfactory." Similarly, another well-known astronomer, in a thorough analysis of the absorption of light in interstellar space, wrote in 1923: "General absorption can at most amount to 2 magnitudes per kiloparsec; the true value is probably less than 0.1 magnitude per kiloparsec." We now know that absorption and scattering in the galactic plane actually amount, on the average, to at least 1.5 mag/kpc, very close to the extreme upper limit of thirty years ago.

In the last three decades enormous strides have been made in determining beyond a doubt the existence of matter between the stars and in estimating the amount of material present. The observational evidence has been obtained with three main techniques. Measures of interstellar emission lines, primarily the Balmer lines and the 21-cm line of neutral hydrogen, have given very basic information on the interstellar hydrogen gas. Spectroscopic measures of absorption lines have given invaluable data on the impurities present in the gas, particularly sodium and calcium. Photoelectric measures of the light from distant stars, which are usually somewhat obscured by the intervening clouds of solid particles, or grains, have indicated the sizes and distribution of these grains. The primary information obtained directly from these observations is brought together in Table 1. While many detailed facts have, of course, been omitted, this table includes most of the general information about interstellar matter which can be obtained directly from the observations, together with well-established physical laws. In particular, results dependent on assumed relative abundances of different atoms have not been included.

It is of interest that modern electronic techniques are responsible for a large part of the

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information in Table 1. Without the photoelectric cell and the electronic equipment needed for microwave reception, the only information remaining in Table 1 would be that obtained with the spectroscope, using this at its ultimate in either speed or resolution. Even here, it would seem that electronic techniques would be preferable. Most of the interstellar lines, other than the standard lines of sodium and ionized calcium, are very weak, usually not much exceeding some 10 mÅ in equivalent width. To detect so weak a line with a photographic spectrograph is difficult, and accurate measures are generally not possible.

TABLE 1

OBSERVATIONAL RESULTS ON INTERSTELLAR MATTER

A. HYDROGEN GAS

Density.	About 1 atom/cm ³ in spiral arms, with much lower values outside arms
Physical state.	Ionization nearly complete within 20–150 parsecs of B and O stars (<i>H II</i> regions) Elsewhere hydrogen is predominantly neutral (<i>H I</i> clouds)
Temperature.	Greater than 1000° in <i>H II</i> regions; temperature about 50° K in dense <i>H I</i> clouds
Velocities.	Circular velocity of galactic rotation; turbulence 5–10 km/sec (r.m.s. radial velocity)

B. OTHER ELEMENTS IN GAS

Density.	Mean density of <i>Na</i> and <i>Ca</i> ⁺ about 3×10^{-9} atoms/cm ³ <i>Fe</i> , <i>Ti</i> ⁺ , <i>K</i> , <i>CH</i> , <i>CH</i> ⁺ , <i>CN</i> present with about same density
Velocities.	<i>Ca</i> ⁺ present in clouds or currents of differing velocities Most of these clouds move with local circular velocity of galactic rotation, plus r.m.s. spread of 5–10 km/sec in radial velocity Straight line in galactic plane near sun intersects 10 such clouds per kiloparsec About 1 per cent of clouds have high random velocities, from 25 up to 95 km/sec Ratio of <i>Ca</i> ⁺ to <i>Na</i> greater in high-velocity clouds than in low-velocity clouds

C. GRAINS

Size.	Mean radius of optically important particles about 3×10^{-5} cm Distribution of radii highly similar in different regions
Density.	Mean space density of optically important particles in local spiral arms about 10 ⁻²⁶ gm/cm ³ ; density much less outside spiral arms Spatial distribution extremely irregular; concentrations range in size from 0.05 to 50 parsecs, with density varying by at least 10 ⁴
Polarization.	Grains somewhat elongated and tend to be oriented perpendicular to local spiral arms

In marked contrast, a photoelectric cell, looking at a width of a tenth of an angstrom and with an integrating time of an hour, could measure the equivalent width of an interstellar line in the spectrum of a 6th-magnitude star with a probable error of only 0.1 mÅ; this calculation is based on the performance of the 100-inch telescope and assumes a light-loss of 90 per cent in the light-path from telescope objective to the photosensitive surface. Such a technique would make possible accurate measures on weak lines, such as the line of neutral calcium at λ 4227, and might even permit a study of the abundance of neutral

oxygen, since the intensity of the forbidden line λ 6300 of interstellar oxygen might be as great as 0.1 m μ in the spectrum of a star about 1 kiloparsec away. Moreover, even for the strong sodium lines, accurate measures of the doublet ratio would be extremely useful in discussing the relative distribution of grains and gas. Evidently it is from the further applications of such electronic techniques that marked progress may be expected in the future observational study of the interstellar gas.

The subject of the present paper is not, however, the important practical problem of observational techniques but rather the fascinating theoretical problem of how matter behaves in interstellar space. The task is the following. Given the data in Table 1, what can we infer about the various physical processes occurring in space, processes which cannot themselves be observed directly? Many fascinating problems arise when we try to carry out this general assignment. Here we shall consider primarily the following two questions: (1) What determines the temperature of the interstellar gas? and (2) How can we explain the random motions of the interstellar clouds? As we shall see, these questions are directly related, since thermal effects apparently are dominant in accelerating the interstellar material.

II. TEMPERATURE OF THE INTERSTELLAR GAS

In many ways interstellar space is as far from thermal equilibrium as can be imagined. The temperature found will depend entirely on the thermometer used. As shown by Eddington (1930) decades ago, a hypothetical material heated only by starlight and absorbing this light with equal efficiency in all wave lengths would cool off by its own radiation to about 3° K. On the other hand, the cosmic-ray particles, which are atoms moving at speeds close to that of light, have kinetic energies corresponding to trillions of degrees. Clearly, the concept of temperature is not very applicable to the stellar radiation field or to the cosmic-ray particles.

a) KINETIC EQUILIBRIUM

When we consider the random velocities of most of the atoms between the stars, we find that these velocities, at least, may be characterized by a temperature. In particular, we shall see that the distribution of the random velocities is closely Maxwellian, exactly as in a system which is in true thermal equilibrium. Thus if we define a kinetic temperature by the equation

$$\frac{3}{2} kT = \frac{1}{2} \overline{m v^2},$$

where v is the three-dimensional random velocity and the bar denotes an average over all atoms, each of mass m , then all properties of the gas depending on random motions of the atoms may be determined from T as though the system were in thermal equilibrium. This quantity T we shall therefore call the "temperature of the interstellar gas."

First, we must show that the velocity distribution is, in fact, Maxwellian. We know that such a distribution will result if elastic collisions predominate over inelastic ones. If kinetic energy is exchanged back and forth among atoms many times, without conversion into radiative energy or internal energy, then the same general probability considerations can be applied as in true thermal equilibrium, and the velocity distribution will be Maxwellian. Such a state of affairs we shall describe as "kinetic equilibrium." Let us therefore examine the relative number of elastic and inelastic collisions.

The rate of energy exchange in elastic collisions may be measured by the time t_E , defined by Chandrasekhar (1942) as the time required for the root-mean-square change of energy by a particle to equal the original energy. The rate of energy loss in inelastic collisions may be measured by the time t_I , defined as the time between inelastic impacts. To obtain the ratio t_I/t_E for electrons, we shall compute this quantity for an electron of kinetic energy $3kT/2$, on the assumption that an inelastic collision involves

an energy loss of half this kinetic energy. The value assumed for the inelastic cross-section may be taken from Spitzer and Savedoff (1953), for an ion of charge Z equal to 1 (with g_B , the weight of the upper level, equal to 3). Resultant values of this ratio are given in Table 2 for different electron temperatures for regions of ionized and neutral hydrogen. In ionized regions the electron density n_e is assumed to be 1 per cubic centimeter, while n_i , the density of ions with which inelastic collisions are possible, is assumed smaller by a factor of 10^3 ; this low abundance of elements other than hydrogen and helium cannot be regarded as proved for the interstellar gas, but seems very probable. In the regions of neutral hydrogen these two densities n_e and n_i are each assumed to equal 10^{-2} per cubic centimeter. In these $H\text{ I}$ regions the density of hydrogen molecules, whose vibrational state may be excited by electrons with more than 0.5 electron volts of energy, is assumed to be 100 times n_e .

The various assumptions made in deriving this table tend to maximize the effect of inelastic collisions, i.e., to decrease t_I . Yet the value of t_I is from 10^2 to 10^9 times greater than t_E . The numbers underlined in the table represent the values for the temperatures regarded as likely. The relatively low value of this ratio when the temperature rises above 1000° , with hydrogen still neutral, results from the excitation of H_2 molecules by elec-

TABLE 2
RELATIVE IMPORTANCE OF ELASTIC AND
INELASTIC ENCOUNTERS

HYDROGEN	VALUES OF t_I/t_E WITH TEMPERATURE OF:		
	100°	1000°	10,000°
Ionized	3.0×10^9	3.6×10^8	<u>4.4×10^7</u>
Neutral	<u>3.5×10^6</u>	3.9×10^5	4.0×10^2

trons. Even in this extreme case, t_I is still sufficiently greater than t_E to insure kinetic equilibrium and a Maxwellian distribution of velocities. Since t_E is only a week or two at most, establishment of kinetic equilibrium should be very rapid. We conclude that the electron-velocity distribution is virtually certain to be nearly Maxwellian throughout the interstellar gas.

For the atoms of the gas, similar conclusions may be demonstrated for the $H\text{ II}$ regions. Moreover, the kinetic temperatures of all the atoms must be closely equal to the electron temperature. In $H\text{ I}$ regions the results are not quite so certain, and, while the hydrogen atoms are likely to have a Maxwellian velocity distribution, their mean kinetic energy may in certain extreme cases deviate significantly from the mean electron energy. Since such deviations do not seem very likely, we may usually neglect them and talk of a single temperature for all particles in the interstellar gas. Even the grains will usually have random velocities given by this kinetic temperature.

b) PROCESSES DETERMINING TEMPERATURE

Once the existence of a temperature has been established for the interstellar gas, it is relevant to investigate the processes which determine this temperature. In principle, these processes are very simple. The gas gains heat by absorption of light from the stars. It loses heat by radiation into space. The temperature automatically adjusts itself so that the heat gained equals the heat lost. If the temperature is too high, then the heat radiated exceeds the heat absorbed, and the temperature falls, while if the temperature is too low, the reverse happens, and the temperature rises. If we know how the absorption and radia-

tion of heat depend on the temperature, we can then find the temperature at which these processes are balanced.

As Eddington (1930) pointed out many years ago, the interstellar gas gains heat from starlight by means of the photoelectric effect. A neutral atom absorbs a photon, and an electron is ejected. The kinetic energy of this free electron is then available for heating the gas. The atoms which are capable of this process spend most of their time ionized. Thus the process consists of an electron colliding with the ion and being captured, emitting a photon. Then a stellar photon of high energy encounters the neutralized atom and is absorbed, with the electron going off with more energy than it had before it was captured. This process of electron capture followed by photoionization can occur with any element. Since hydrogen and helium are assumed to be vastly more abundant than any other elements, these two types of atoms provide most of the heating for the interstellar gas. Strömgren (1939) has showed that the ultraviolet radiation capable of ionizing hydrogen or helium is confined to roughly spherical regions around the early-type stars, a result given in Table 1. This theoretical prediction has been beautifully confirmed by observations made by Morgan and his collaborators at the Yerkes Observatory on such regions nearby and by Baade at the Mount Wilson and Palomar Observatories on such regions in M31. It follows directly that most of the heating of the interstellar gas must occur in these regions.

The cooling of the gas by radiation is quite a different story. Here atomic hydrogen plays a very minimum role, since this atom is a very poor radiator in visible and infrared light. As shown by Menzel and Aller (1941) for planetary nebulae, the dominant process of cooling is excitation of an atom by electron impact, followed by radiation of a photon, which carries away into space the energy lost to the atom by the colliding electron. All the excited states of the hydrogen atom lie some 10 volts or more above the ground level. Hence atomic hydrogen cannot radiate under electron bombardment unless the electrons have some 10 volts of energy, corresponding to a temperature well above 10,000° K. In helium the situation is even more extreme, with the lowest excited state lying about 20 volts above the ground level. Most other atoms, neutral or ionized, have levels with excitation energies ranging from a hundredth of an electron volt to several electron volts. These atoms can provide an important source of cooling. In addition, molecules and grains can radiate in the infrared and must also be considered as cooling agents.

c) TEMPERATURE OF *H II* REGIONS

Since oxygen is probably more abundant than any of the other atoms possessing low-lying energy levels and since most of the oxygen atoms in *H II* regions are probably singly ionized, the excitation of the O^+ excited level, 3.31 electron volts above the ground-level, is likely to be one of the chief sources of cooling in these regions. An atom excited in this way will jump down, after a wait of several hours, emitting a photon in the forbidden lines at λ 3727. Cross-sections for excitation of this level by electrons have recently been computed by Seaton (1953), who estimates an accuracy of about 40 per cent in his results. Since many previous computations gave results which were too great by an order of magnitude, the accuracy claimed by Seaton should represent a very great gain over previous work. From his results we can compute L_{ei} , the energy lost per electron per second in collisions with oxygen ions. From known quantum-mechanical formulae we can compute G_{ep} , the energy gained per electron per second in radiative encounters with protons, including energy losses in free-free transitions as well as electron captures and subsequent re-emission. The results are shown in Figure 4, where the dotted line represents G_{ep} , with the dashed line, L_{ei} . In this computation the proton density has been set equal to 1 per cubic centimeter, with the density of oxygen ions, to 10^{-3} per cubic centimeter. The distribution of ionizing radiation is taken to be that near a star of surface temperature 30,000°, corresponding to a star of spectral type about O9. The rise of the energy gain, G_{ep} , at the lower temperatures is due to the increase in electron-capture

cross-section with decreasing electron velocities. A slow electron is much more likely to be captured than a fast electron. The steep rise of L_{ei} with increasing temperature results from the fact that, at the temperatures shown, only a very small fraction of the electrons present have the 3.31 electron volts of energy required to excite the singly ionized oxygen atom. As the temperature increases, this fraction rises sharply, with a resultant rise in the rate of cooling.

Figure 1 shows that the equilibrium temperature under this assumption is about 8000° K. More important, the figure shows that large changes in the relative abundance of oxygen to hydrogen will not affect the temperature very greatly. If, for example, we

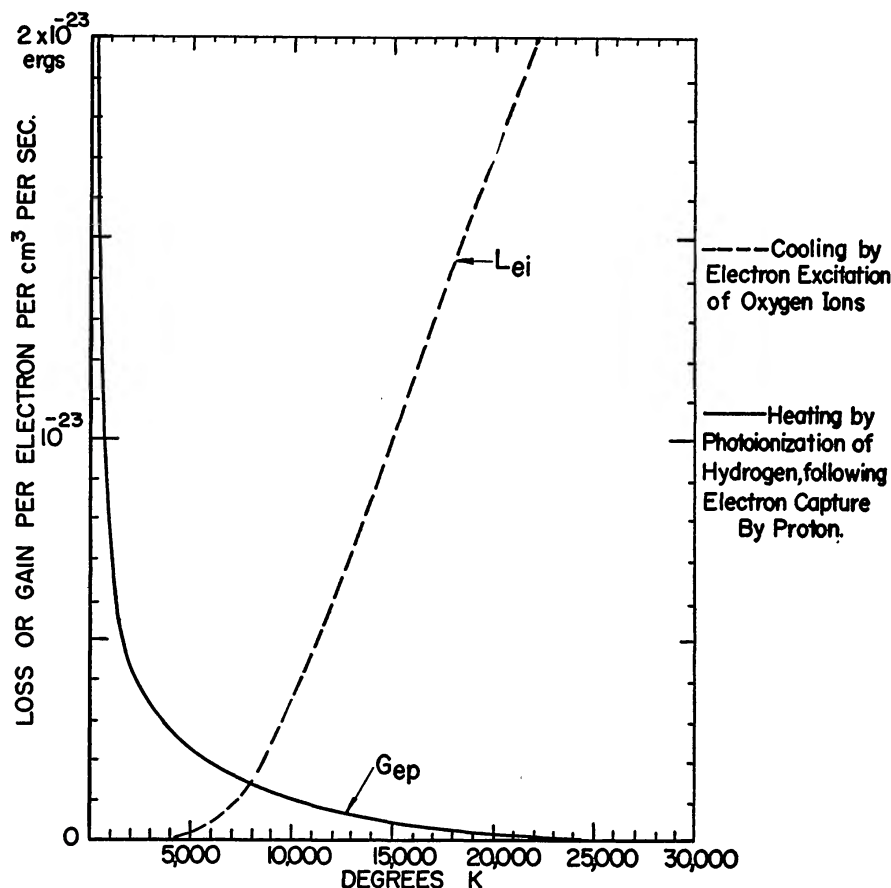


FIG. 1.—Heating and cooling in regions of ionized hydrogen

assume that this relative abundance is uncertain by a factor of 2, then the equilibrium temperature will lie between 7000° and 9000° . Evidently, if there is any appreciable amount of singly ionized oxygen present, the temperature cannot be much greater than about $15,000^{\circ}$ K. Temperatures much lower than 8000° would be possible if there were some other cooling agent whose efficiency held up at lower temperatures. Neutral atoms are relatively ineffective, and the only other ion with probable high relative abundance and suitable low-lying excited levels is singly ionized nitrogen, which has an excited level at 1.89 electron volts. This excitation energy is a little over half the energy of the first excited level of O^{+} . Electron excitation of this level would depress the temperature to about 5000° K, if the abundance of N^{+} were as great as that assumed here for O^{+} . If this happened, very few electrons would have enough energy to excite the oxygen ions, and

the forbidden lines of O^+ would not occur. The fact that these lines are actually observed in considerable strength indicates that the temperature is probably at least 8000° and either that the collisional cross-sections are much less than computed or that the abundance of N^+ is substantially less than that of O^+ . The fact that the ionization potential of N^+ is 5.5 volts less than that of O^+ might account for this difference in relative ion abundance.

Evidently we are far from a precise numerical agreement between theory and observation for the temperatures of $H\ II$ regions. The important physical processes seem clear, however, and a temperature somewhere in the general neighborhood of $10,000^\circ\text{ K}$ seems firmly indicated.

d) TEMPERATURE OF $H\ I$ REGIONS

When we consider the regions where hydrogen is neutral, we find an entirely different picture. The chief heating mechanism, absorption of ultraviolet radiation by hydrogen atoms, is now absent, since the entire ultraviolet end of the spectrum, beyond 912 Å, is completely missing as a result of the high ultraviolet opacity of the neutral hydrogen gas. In addition to hydrogen, the elements helium, nitrogen, oxygen, and neon will be completely neutral. Of the more abundant elements, carbon, with its ionization potential 2.3 electron volts less than that of hydrogen, can be ionized. Thus the free electrons will come from carbon, together with silicon and the metals, and the primary source of heating will be the photoionization of these same atoms. Cooling will be produced when an electron excites the low-lying levels of these ions, exactly as before. Since the heating has diminished so markedly, while the physical processes producing cooling are relatively unchanged by the neutralization of the hydrogen, it is evident that the temperature must drop until the electrons no longer have enough energy to excite the low-lying levels. We shall see that the resultant equilibrium temperature is in the neighborhood of 50° K .

If we neglect the presence of the neutral hydrogen atoms for the moment, the physical reason for this low temperature of $H\ I$ regions is the relative inefficiency of heating by radiation as compared to cooling. We have seen that heating requires, first, that an electron be captured by an ion, in order that this same electron may be ejected from the atom by a photon of starlight. Electron capture, with the emission of radiation, is a very inefficient process. For electrons whose kinetic temperature is about $10,000^\circ\text{ K}$, the cross-section for capture is about 10^{-21} cm^2 , much less than the geometrical cross-section. Excitation of an ion by an electron is a very much more likely process, if the atom has a level whose excitation energy is less than the electron kinetic energy. The cross-section for such an event is about 10^{-17} cm^2 for electrons at $10,000^\circ$; this value is somewhat less than the geometrical cross-section of a neutral atom, but greater than the cross-section for radiative capture by a factor of 10,000. For every electron that is captured and then absorbs a stellar photon and heats up the gas, 10,000 electrons will excite the ionized atom, if the excited levels have energies low enough. Evidently the gas will cool until the electrons no longer have enough energy to excite the ions. In $H\ II$ regions the heating is done by protons, which are at least 1000 times more abundant than the atoms doing the cooling. Thus with a moderate drop of the rate of cooling, produced by a fall of the temperature to about $10,000^\circ$, equilibrium is reached. In $H\ I$ regions, where the ions responsible for the cooling must also provide the heating, the temperature must drop much further.

If the only low-lying excited levels were those we have already discussed, with excitation energies of several volts, the temperature would not have to drop very far before the rate of cooling fell practically to zero. In fact, most ions have low-lying levels about a hundredth of an electron volt above the ground-level, and the excitation of these can produce cooling even at 100° K . The heat lost to the gas in each excitation is small, and for this reason these levels are unimportant in $H\ II$ regions. In $H\ I$ regions, where both

heating and cooling are relatively much slower, these low-lying excited levels are very important.

To illustrate the type of behavior that may be expected, we may compute the heating and cooling for a gas composed of electrons and singly ionized carbon atoms. Since carbon is the most abundant atom that can be ionized in the $H\ I$ region, other elements may at first be neglected. The ion C^+ has an excited level 0.0079 electron volts above the ground level. No information is available on the cross-section for collisional excitation of this level, but if we take reasonable values, following Spitzer and Savedoff (1953), we obtain the results shown in Figure 2. Here G_{ei} , shown by the solid line, represents the

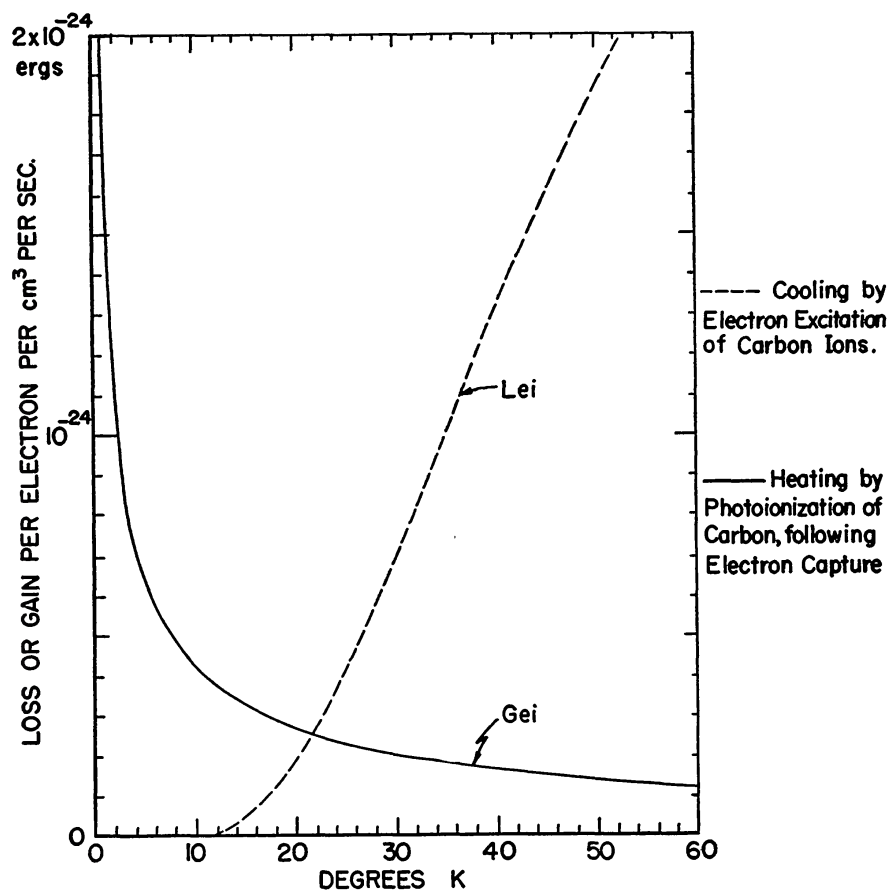


FIG. 2.—Heating and cooling by electrons in regions of neutral hydrogen

gain in energy per electron per second resulting from electron capture and subsequent reionization; L_{ei} , shown by the dashed line, represents the energy loss per electron per second resulting from ion excitation. To fix the vertical scale, the ion density has been set equal to $5 \times 10^{-3}/\text{cm}^3$; the relative position of the two curves is unaffected by the ion density. The color temperature of the ionizing radiation is taken to be $20,000^\circ \text{K}$.

Figure 2 indicates an equilibrium temperature of only 22°K . Again we see that relatively large changes in the assumed cross-section for collisional excitation will lead to only a small change in the equilibrium temperature. However, carbon ions may be much less abundant than we have assumed. It is possible that the carbon atoms are mostly neutral, although this does not seem very likely in a typical interstellar gas cloud. Another possibility is that a large fraction of the carbon atoms may be locked up in the

grains. For conditions in a typical gas cloud, a carbon ion will collide with a grain about once every 3×10^8 years, and there has thus been plenty of time for atoms to stick to grains. The rate at which atoms are given off from the grains depends partly on the rate of collisional evaporation, a process analyzed in detail by Oort and van de Hulst (1943), and partly on the rate of photodissociation at the surface of grains, a process which may also be of importance. Since these rates are difficult to compute theoretically, no definite conclusions can be drawn. While the observation of molecular CH in interstellar clouds indicates that some carbon vapor must be present,¹ the possibility that most of the carbon atoms may be locked up in the grains can certainly not be excluded.

To digress for a moment from the subject of interstellar temperatures, it may be noted that analysis of interstellar sodium and calcium suggests that many of the calcium atoms, also, are locked up in the grains. We have seen in Table 1 that the ratio of calcium ions to sodium atoms is higher in the clouds of high velocity than in the low-speed clouds. When these ratios are interpreted in terms of the ionization equilibrium theory, as applied by Strömgren (1948) to these conditions, we find that the ratio of calcium atoms, in all stages of ionization, to the corresponding number of sodium atoms has nearly the same value in the high-velocity clouds as in the earth and the stars. In the low-velocity clouds, on the other hand, this ratio is abnormally low. The result is consistent with the belief that in the low-velocity clouds calcium atoms are mostly locked up in the grains, while the sodium atoms are not. If the sodium atoms are expelled from grains, on absorption of a photon in the near ultraviolet, while calcium atoms are not, this result would be consistent with physical expectations. The normal ratio in high-velocity clouds could then be attributed to general evaporation or dissociation of the grains produced at the same time that the clouds were accelerated, since, as we shall shortly see, acceleration is apparently produced by an intense field of ultraviolet radiation. This working hypothesis seems to have a certain attractiveness.

Returning, now, to interstellar temperatures, if we admit the possibility that carbon ions may not be present in appreciable abundance, we must then consider the effects produced by other ions. The next most abundant elements with such low-lying levels in the singly ionized state are silicon and iron. Since the excitation energies of the lowest excited levels in these ions are 0.035 and about 0.05 electron volts, some five times the corresponding excitation energy in the carbon ion, the equilibrium temperature will be roughly five times as great as the value shown in Figure 2, or roughly 100° K. Evidently, a temperature not much greater than 100° K seems indicated in an $H\text{ I}$ region.

We have neglected so far the presence of neutral hydrogen atoms in these $H\text{ I}$ regions. Since these atoms probably outnumber all others except helium, by a factor of about 1000 to 1, this neglect may not always be justified. In fact, collisions involving hydrogen atoms or molecules may under certain conditions provide the dominant source of heating and cooling.

To consider heating first, a hydrogen atom may be ionized by a passing cosmic-ray particle. If the intensity of cosmic rays throughout space is the same as the measured intensity striking the earth, the kinetic energy carried off by the free electron amounts, on the average, to 4×10^{-30} ergs per neutral hydrogen atom per second. This value is shown by the solid line in Figure 3. To compare this rate of heating with that shown for electrons in Figure 2, we must multiply G_{ei} by n_e and G_{He} by n_H to obtain the energy gained per cubic centimeter per second. If the ratio n_e/n_H is about 2×10^{-4} , then the cosmic-ray heating amounts to only one-tenth the heating by starlight at an electron temperature of about 50° and is therefore unimportant on the basis of these assumptions. However, the cosmic-ray intensity in interstellar space is still quite uncertain, and the existence and magnitude of this supplementary heating are both quite uncertain.

Of the cooling mechanisms involving neutral hydrogen, one process is relatively sure,

¹ I am indebted to Dr. A. Schlüter for this suggestion, as well as for other helpful comments concerning this paper.

the other uncertain. We know that solid particles or grains are present in space, and their mean density is moderately well known from the work of van de Hulst (1949). When a hydrogen atom collides with a grain, it will tend to lose its initial kinetic energy and to leave with an energy characteristic of the internal temperature T_g of the grain. The value of T_g is not certain, but for any assumed T_g the rate of cooling may be computed with some accuracy.

The dashed line in Figure 3 shows the rate of cooling by this process for a grain temperature T_g of 20° K and for a particle density of grains ten times the average. For gas

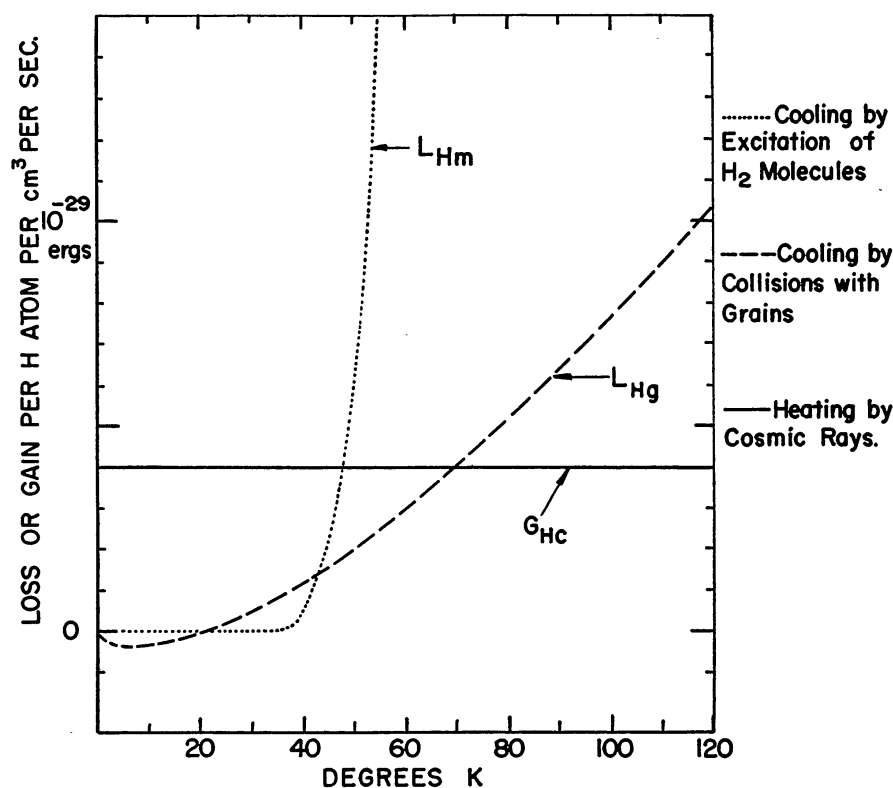


FIG. 3.—Heating and cooling by hydrogen atoms

temperatures considerably in excess of T_g , the computed cooling does not depend on T_g and should be reliable. The equilibrium temperature, if electron processes are unimportant and G_{Hc} and L_{Hg} are dominant, is about 70°. With a higher particle density for the grains, T would be reduced.

One last cooling process must be considered. If hydrogen molecules are present in the gas, collisions with hydrogen atoms will excite the molecular rotational levels and lead to radiation in the infrared. The rotational spectrum of the hydrogen molecule is not observed in the laboratory, as the transitions are forbidden. In interstellar space, however, the transition will take place, after a lapse of from one to a thousand years. The computed rate of cooling, for a particle density of 1 hydrogen molecule per cubic centimeter, is shown by the dotted line in Figure 3. Evidently, for temperatures greater than 50° K the cooling by this process is very rapid. We have no certain evidence that molecular hydrogen is present in interstellar space, but its formation seems likely, since the grains should provide an effective catalyst. If molecular hydrogen is present, it may well have no great effect on the equilibrium temperature, since cooling by ions and grains is more

efficient at temperatures between 20° and 40° K. If for some reason the temperature is increased, then the molecules come into action, cooling the gas much more rapidly than would otherwise be possible. For example, if a shock wave heats a gas cloud to 5000° , cooling by molecules will depress the temperature to about 2500° in roughly a thousand years, if the hydrogen density is 10 atoms and 1 molecule per cubic centimeter. This result is in contrast to the million years required for the same cooling without molecules. Since a thousand years is a very short time in interstellar space, it is clear that molecular cooling of the interstellar gas can be very rapid.

This discussion refers entirely to equilibrium conditions, with both heating and cooling produced by local influences. An additional source of heating in $H\text{ I}$ regions, recently proposed by Kahn (1953), is provided by collisions between clouds. Such collisions will certainly produce a kinetic temperature of several thousand degrees at the point of impact. At this high temperature, however, the increased rate of cooling may get rid of the additional thermal energy rather rapidly. Detailed computations on the mean temperature of $H\text{ I}$ clouds are not yet available; it is readily shown that under these conditions such an average temperature cannot exceed about 200° K.

While the theoretical study of interstellar temperatures has not yet yielded precise numerical values, a large difference of temperature between $H\text{ II}$ regions and dense $H\text{ I}$ clouds seems firmly established. With a temperature of about $10,000^\circ$ in $H\text{ II}$ regions and perhaps about 50° in the $H\text{ I}$ clouds, the ratio of temperatures amounts to a factor of about 200. Since radio measures of the hydrogen emission line at 21 cm confirm the low temperature of the $H\text{ I}$ clouds, while the appearance of the forbidden line of O^+ confirms the high temperature of $H\text{ II}$ regions, this difference of temperature, which was first predicted theoretically, may be taken as observationally confirmed. As we shall see, this phenomenon should have important cosmogonic consequences.

III. MOTIONS OF THE INTERSTELLAR GAS

The observations summarized in Table 1 indicate that the interstellar gas, in addition to sharing in the general galactic rotation, is in a state of chaotic or turbulent motion. The average clouds have root-mean-square radial velocities between 5 and 10 km/sec, while occasional clouds have velocities ranging up to nearly 100 km/sec. Unlike the stars, the gas clouds will collide with one another relatively frequently, perhaps as often as once every 10,000,000 years. Since each collision must be highly inelastic, the motions would quickly die out if there were no force to sustain them. We shall see that, in a general way, the temperature differences which have been demonstrated between different parts of the gas are capable of maintaining these cloud velocities.

a) PRESSURE EQUILIBRIUM

Let us now examine the physical processes occurring in a gas in which there are large differences of temperature. One important effect which such a gas will show will be a tendency toward equalization of pressure in different regions. Since the gas pressure is proportional to the product of the density and the temperature, it follows that if the density is uniform, the temperature differences will produce large differences in pressure. The regions at high pressure will then tend to expand, compressing the remainder of the gas. If, for example, a region of the earth's atmosphere is suddenly heated to 200 times the temperature of the surrounding atmosphere, a violent explosion will result. If the heated region is 100 meters on a side, the effect will be comparable to the atomic bomb. Similarly, an interstellar cloud at high temperature will tend to expand.

In the absence of any abrupt change of temperature with time, such as is produced by a nuclear detonation, the gas will tend to come to pressure equilibrium. The high-temperature gas will expand until its pressure is equal to that in the surrounding region, and similarly the low-pressure gas will tend to be compressed. The speed with which pressure is equalized across the gas is given by the velocity of sound, and a pressure disturbance

will propagate outward at this velocity. In $H\ II$ regions the sound velocity is about 17 km/sec, while in $H\ I$ regions we obtain the much smaller value of 0.8 km/sec. Then in 10,000,000 years, which is about the time between collision among clouds, pressure should begin to be equalized over about 170 parsecs if the hydrogen is ionized, and about 8 parsecs if the hydrogen is neutral. The greater value is comparable with the dimensions of the luminous $H\ II$ regions, while the smaller value is about the diameter of the small obscuring clouds, which presumably contain neutral hydrogen. While complete equality of pressure throughout the gas is not to be anticipated, we may expect a considerable tendency toward pressure equilibrium.

Such a tendency predicts at once that the regions of neutral hydrogen should be several hundred times as dense as the ionized regions, since this is about the ratio of probable temperatures. We thus arrive at a picture of $H\ I$ clouds surrounded by a rarefied medium of much lower density. While the observations cannot be said to confirm such a picture unequivocally, Strömgren (1948) has shown, from an analysis of the interstellar absorption lines based on very reasonable assumptions, that the density of hydrogen within the clouds is probably about 10 atoms per cubic centimeter, while the density between the clouds is probably less by a factor of 100 or more. Actually, the atoms in this tenuous intercloud medium could be mostly neutral and still at a relatively high temperature, since at so low a density the time required for cooling, in the absence of H_2 molecules, is about a million years. We may conclude that as far as the data go, they are not inconsistent with the suggestion that the pressure in the interstellar gas tends to be uniform.

b) THERMAL ACCELERATING FORCES

We turn now to a consideration of the various ways in which thermal effects in the interstellar medium may produce motions. One mechanism is evident from the study of winds in our own atmosphere. These winds are entirely driven by thermal effects. Air is heated at the ground and expands under conditions of constant pressure. The expanded air is more buoyant than the surrounding denser air and tends to rise. The resulting air currents are then profoundly modified by the earth's rotation to give the observed winds. In the same way, interstellar gas which has been heated by an early-type star will tend to rise away from the galactic plane, buoyed up by the surrounding denser gas. Because of the spotty distribution of the O and B stars, the resultant cosmic winds should not be so systematic as the terrestrial winds, but they might be expected to become important near clusters of early-type stars. The gas velocity produced in this way might be expected to be comparable to the sound velocity in $H\ II$ regions, or about 17 km/sec. This mechanism is clearly inadequate to account for the occasional much higher velocities observed by Adams (1949).

A second mechanism, which has been proposed by Oort (1953) and by Biermann and Schlüter (1953), relies on the dynamical effects of sudden heating. We have already seen that if the temperature of a gas is abruptly increased, an explosion results. One means for a sudden increase in temperature is the birth of one or more luminous O stars in a dense cloud. It is now rather generally accepted that the early-type stars are forming continuously from interstellar matter in the spiral arms, and the natural place for such stars to form is inside relatively dense clouds of neutral hydrogen. How rapidly the luminosity of a star will rise at its birth is uncertain, but it seems likely that the starlight, at least in the far ultraviolet, is "turned on," so to speak, relatively abruptly, perhaps in less than 10^5 years. The temperature and pressure in the surrounding clouds will rise equally abruptly. The result should be a violent explosion, shooting gas in all directions.

If there were no additional source of heat for the gas, once it was heated initially, the expansion would be adiabatic, and the gas would cool. In this case the velocity which might be attained by the ejected material would not exceed the sound velocity. Actually, the explosion is probably sufficiently leisurely so that the gas is maintained at a constant temperature by the heating and cooling mechanisms discussed above. In this isothermal



FIG. 4.—Detail of emission nebula M16, photographed with the Hale 200-inch telescope

case the expansion velocity may considerably exceed the sound velocity, though velocities exceeding 50 km/sec are not likely to be reached in this way.

A third mechanism, which should be capable of accelerating a few small clouds to very high velocities, might be called the "interstellar rocket." In an ordinary rocket, hot gases are ejected in one direction, accelerating the rocket in the other direction. The velocity attained may be much greater than the ejection velocity, provided that the amount of material ejected is larger than the final mass of the rocket. A dense cloud of neutral hydrogen constitutes a natural rocket when placed near a luminous star of high surface temperature. The stellar radiation heats up the surface of the cloud, on the side facing the star, to about $10,000^\circ$. The heated material expands and shoots away from the cloud; since only one side is heated, the gas will stream away predominantly in one direction—toward the hot star. The recoil from this stream of gas will then accelerate the cloud away from the star. The ejection velocity will be comparable with the speed of sound in an $H\ II$ region, and if the cloud loses all but 1 per cent of its mass in this way, the remnant may be accelerated to a speed of about 80 km/sec, comparable with the highest speeds observed by Adams. This result assumes that the cloud is initially stationary relative to the star; if it is approaching the star initially, the final velocity is somewhat less.

With the explosion around a newly born O star accounting for the bulk of the cloud velocities and with supplementary rocket acceleration accounting for the occasional clouds of very high velocity, it appears from some rough computations by Oort and Spitzer (1954) that the observed cloud velocities may be accounted for. One direct result of the theory is that the clouds of very high velocity should mostly be approaching the earth rather than receding from it. Such clouds do not retain their high velocity very long, and they are most likely to be seen when they lie in the line of sight between the earth and the star whose radiation is responsible for their motion. Clearly, they will be moving away from the star and toward the earth, and their radial velocities will be negative. Blaauw (1952) and Searle (1952) have noted the preponderance of negative cloud velocities, which are about twice as numerous as positive velocities for clouds with random velocities in excess of 15 km/sec. In terms of the present picture, this result finds a natural explanation.

c) RALEIGH-TAYLOR INSTABILITY

We have seen that the relatively dense clouds may be accelerated outward by the high pressure of the heated gas surrounding a hot star. If this picture is correct, one puzzling feature of the observed interstellar clouds may find a very natural explanation. It has been known for some time that many of the bright nebulae are characterized by tongues or "elephant trunks" of obscuring matter, extending from the surrounding dark nebulae into the emitting regions and pointing in the general direction of the exciting star. Figure 4, which reproduces a plate taken by Humason with the 200-inch Hale telescope at the Palomar Observatory, shows a prominent feature of this sort in the emission nebula M16, NGC 6611.²

A recent analysis by Frieman (1954) shows that spikes of this approximate size and shape are a natural result of an assumed expansion of the hot gases in the luminous nebula. When the gas is heated and expands, it becomes less dense than the cool clouds which surround the nebula and which are being pushed radially outward. Thus at an early stage in the expansion we find a light gas pushing a denser one. It was shown theoretically by Lord Rayleigh (1899) many years ago that this state of affairs was unstable. The origin of this instability is physically obvious in the case of a thick layer of water supported from below by a layer of air. It is clear that any small displacement in an initially plane interface between the water and the air will grow until the water and air have finally exchanged places. This subject has been investigated anew by Taylor (1950)

² I am much indebted to Dr. Humason for his kind permission to include this reproduction here.

and by Lewis (1950), who obtained photographs of the interface between a liquid and a gas when the gas was pushing the liquid.

The results of the experiments by Lewis are portrayed in Figure 5. The light fluid below is pushing up the denser one above, and either supports it against the vertical force of gravity or accelerates it upward. In any case, the successive diagrams in Figure 5 indicate the progressive development of the Rayleigh-Taylor instability. When the disturbance is small, the first-order theory of Rayleigh and Taylor is applicable, and the disturbance increases exponentially with time. When the disturbance becomes compa-

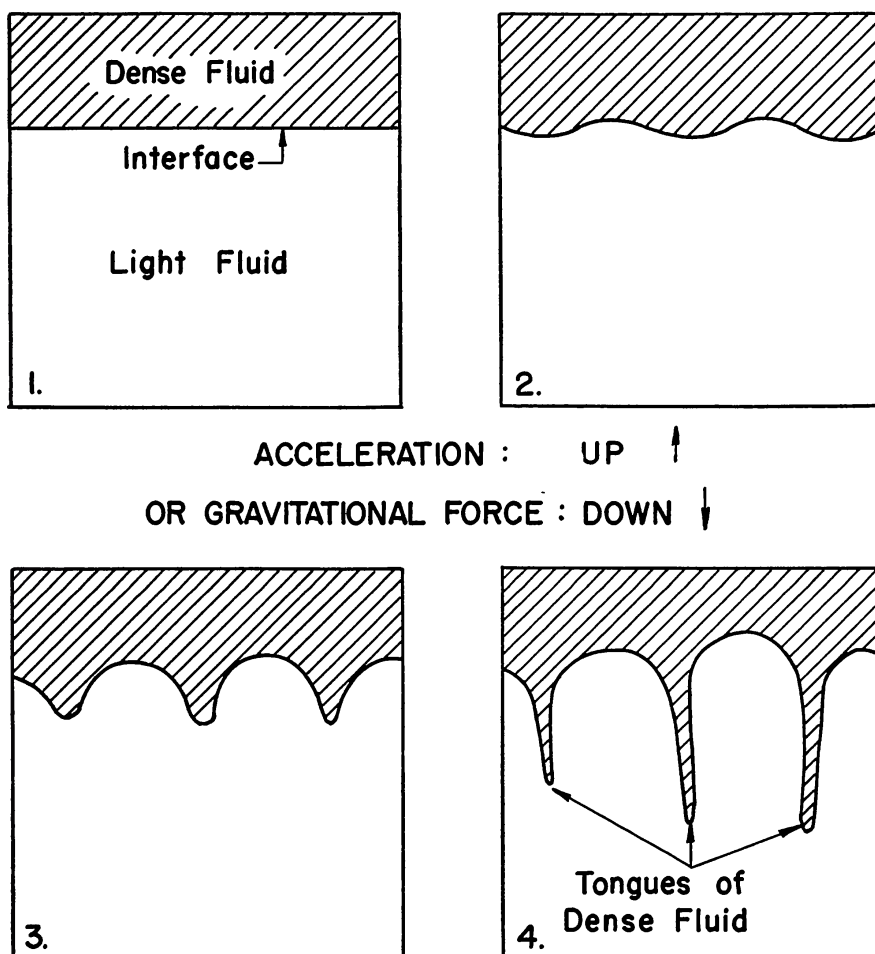


FIG. 5.—Development of Rayleigh-Taylor instability

able with the wave length, the first-order theory is no longer applicable; but a theory of finite displacements developed by Layzer (1954), Frieman (1954), and others is in satisfactory agreement with the observations. According to this theory, thin spikes of the dense material fall through the lighter material, while thicker columns or "bubbles" of light material move into the heavier fluid. The problem is complicated by another type of instability which arises at the surface of the spikes, resulting from the discontinuity of velocity across the surface, and a great complication in the end result is entirely consistent with the theory.

Uncertainty about the physical conditions in actual emission nebulae and lack of

knowledge as to the initial irregularities when expansion began prevent a precise comparison between theory and observation. However, the general order of magnitude of the observed spikes and bubbles seems consistent with the theory. If the general point of view adopted here is correct and heated gases around hot stars are accelerating the surrounding dense clouds, spikes of this sort seem inevitable. The general agreement here between theory and observation lends added support to this whole viewpoint.

d) MAGNETIC FIELDS AND SPIRAL ARMS

Last, we come to one of the most fascinating topics encountered in the discussion of interstellar motions. The work of Alfvén (1950) and Fermi (1949) has shown that if a magnetic field is present between the stars, there must be a very intimate connection between this field and the cloud motions, since, under conditions in interstellar space, ionized particles cannot stray very far from a particular line of magnetic force. As a result, either the motions will greatly distort the magnetic field or the magnetic field will restrain the motions. A magnetic field of about 10^{-5} gauss seems to provide the dividing line. A field much less than this will have no effect on the main motions of the interstellar gas, while a much greater field will entirely control these motions.

The only clear evidence for the existence of an interstellar magnetic field is the polarization of light from reddened stars, a spectacular discovery by Hiltner (1949 and 1951) and by Hall (1949 and 1950). According to work by van de Hulst (1950), the amount of polarization can be explained if the grains are elongated and at least partially oriented. The only mechanism for orienting the grains which seems quantitatively plausible is by means of a magnetic field. An alternative theory, attributing the orientation to systematic motion of the grains through the gas, has been put forward by Gold (1952). According to Davis (1954), there is serious question as to whether the polarization data can actually be explained on the basis of Gold's ingenious theory. For magnetic orientation, two theories have been put forward. The one by Davis and Greenstein (1951) orients the particles perpendicular to the magnetic field by the dissipative mechanism of paramagnetic relaxation. The Spitzer-Tukey (1951) theory orients ferromagnetic grains parallel to the magnetic field in somewhat the same way that a compass is aligned parallel to the earth's magnetic field. However, both theories require rather high fields, greater than 10^{-5} gauss for the Greenstein-Davis version and still another order of magnitude higher for the Spitzer-Tukey version.

There is some hope that the interstellar polarization can be explained with much lower fields, perhaps less than 10^{-6} gauss. Gorter has suggested informally that tiny ferromagnetic particles, so small that they constitute single domains, might be subject to a ferromagnetic relaxation many orders of magnitude greater than the paramagnetic relaxation. In the absence of laboratory evidence, which would require experiments on ferromagnetic particles no larger than the interstellar grains, this suggestion provides only a preliminary working hypothesis, which, if verified, would much simplify the entire subject. If the orientation method proposed in Pasadena can be applied to the ferromagnetic grains proposed at Princeton, the reduced magnetic field required would seem much more plausible than the larger fields which now are needed.

In any case, it seems clear from the observations that the magnetic field is intimately connected with the spiral arms, as shown in detail by Hoag (1949). If we look along the spiral arms (parallel to the axis of the arm), the polarization is small and randomly oriented, while the maximum polarization is found for light passing transversely across the spiral arm (perpendicular to the axis). Assuming orientation by some dissipative process, either paramagnetic or ferromagnetic, we see that the magnetic lines of force are preponderantly parallel to the axis of the spiral arm. This result, if accepted, is obviously a very basic one in our understanding of the nature of spiral arms.

There are two different ways in which this result may be interpreted. The first, due to Chandrasekhar and Fermi (1953), assumes that an approximately uniform and homoge-

neous magnetic field is present within the spiral arm, the line of force being mostly parallel to the axis of the arm. To maintain these lines of force parallel despite the motions of the clouds requires a field of 1.8×10^{-5} gauss, if we take, following Blaauw (1952), a root-mean-square cloud velocity of 7 km/sec in the line of sight, or 12 km/sec for the corresponding three-dimensional mean. This field is probably strong enough to orient the grains by the Davis-Greenstein mechanism.

There are several objections that may be made to this picture. First, it is rather surprising that such a large uniform field does not produce more striking effects in the appearances of the diffuse nebulae. Second, it is rather difficult to understand how such a uniform field could ever have been produced. Third, it is not a simple matter to prevent the lateral expansion of a spiral arm with so strong a uniform field. All these arguments are rather theoretical, however, and by no means conclusive.

There is an entirely different point of view from which these polarization results may perhaps be viewed. As Spitzer and Tukey (1951) have suggested, the magnetic field may be assumed to be highly chaotic, averaging out to zero over distances of less than 100 parsecs, but with a tendency for the lines of force to lie parallel to the spiral arm. The distribution of magnetic fields, exactly like the distribution of stellar velocities, would be ellipsoidal, with the average field, like the average random velocity, canceling out to zero in the average. The major axis of the magnetic ellipsoid would be parallel to the axis of the arm, while for the velocity ellipsoid the major axis points to the galactic center. The lines of force in such a distribution may be visualized by taking a loose tangled mass of string and stretching the entire mass in a particular direction. On the average, the strings will tend to be parallel to the direction of stretching.

The chief advantage of such a configuration is that this is exactly the type of distribution that might be expected to arise in a spiral arm. Batchelor (1950) and Schlüter and Biermann (1950) have shown that the random motions of the interstellar clouds will pull out the lines of force and produce an exponential increase in the magnetic-field strength until fields of the order of 10^{-6} gauss result. Such fields would apparently have a small scale and a spherical distribution. As implied by Cowling (1953), the differential rotation will stretch out a spiral arm, and this large-scale stretching of the lines of force will tend to produce an ellipsoidal distribution of magnetic fields, with the major axis of the ellipsoid parallel to the axis of the arm.

The chief disadvantage of this type of magnetic field is that the root-mean-square excess field parallel to the axis of the arm is not likely to be very great, perhaps no greater than 10^{-6} gauss. Such a field would be too weak, by at least an order of magnitude, to explain the observed polarization on the Davis-Greenstein theory. If ferromagnetic grains are present, however, and if ferromagnetic relaxation is as strong as proposed by Gorter, a field of about 10^{-6} gauss would be about right to explain the polarization data. Evidently, the model of small-scale magnetic fields, while it has many attractive features, is at best only another working hypothesis at the present time.

One final consequence of interstellar motions must be pointed out. According to Fermi (1949 and 1954), motion of the interstellar clouds can accelerate charged particles and account for the observed cosmic-ray spectrum. At the moment, this theory seems to offer the best hope of accounting quantitatively for the existence of cosmic rays. If this theory proves correct, it should be possible to use the existence of cosmic rays to deduce certain properties which the interstellar magnetic field must possess. At the present time there are too many uncertainties in the subject to permit any very definite conclusions in this respect.

In conclusion, we have seen that when an early-type star appears in a cloud of neutral gas, either by star formation or by relative motion, the photoionization of hydrogen has many important consequences. The free electrons ejected carry off several electron volts of energy and gradually heat up the material from its initial temperature of about 50° to roughly $10,000^\circ$ K. As the pressure increases by a correspondingly large factor, very large

dynamical effects appear. The hotter gas pushes the cooler gas away, and the resulting instabilities account for at least some of the complicated contours of observed emission nebulosities. The resultant motions of the clouds may be responsible for the growth of an interstellar magnetic field. The motions of the clouds in the presence of such a field may well be responsible for the acceleration of a relatively small number of charged particles to cosmic-ray energies. Thus a wide variety of cosmic processes over enormous reaches of space may ultimately find a simple explanation in terms of temperature differences in the interstellar gas.

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