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Recent Work on the Interstellar Medium*

NANNIELOU H. DIETER AND W. MILLER GOSS
Radio Astronomy Laboratory, University of California, Berkeley, California

Emphasis in this review of current problems in the study of the interstellar medium is on a few specialized topics. The first treated is the problem of the cloud structures and the velocity fields in the interstellar gas. Another section deals with the observations suggesting the presence of dust as well as gas in the medium and with the proposed nature of the dust grains. These grains were the first indicators of the presence of a general galactic magnetic field and are believed to be catalytic agents in the formation of molecules in the gas. The status of current observational investigations of the magnetic field and of current theoretical studies of the formation of interstellar molecules is described. Finally, very recent observations in the microwave spectrum of the hydroxyl radical are outlined. These suggest the availability of new and surprising information about conditions in the interstellar medium.

I. INTRODUCTION

A. Outline

The space between the stars in our galaxy is not an empty wasteland, but a region filled with gas and dust. This interstellar material is not distributed uniformly, nor are its chemical and physical properties homogeneous throughout the galaxy. Local concentrations of matter seem to be the rule rather than the exception. The particle density in the interstellar medium is everywhere very small compared with that in stars. The mean concentration is about 0.1 atoms/cm^3, and the maximum is about 100 atoms/cm^3 in some large complexes of interstellar clouds, while the most tenuous observable regions of the outer solar atmosphere, for example, contain 10^6 to 10^8 atoms/cm^3.

Yet the total amount of this gas is very great, from one to ten percent of the galaxy, and a study of this gaseous component of the galaxy is critical to the understanding of the distribution and physical condition of matter in our, or any other, galaxy. The study of the physics of the interstellar medium is beset by enormous difficulty because of the low concentration of matter (which requires observing over a great volume to obtain detectable results), and because of the associated great deviations from local thermodynamic equilibrium. To illustrate the problem, so diffuse is the gas that the mean free path of a hydrogen atom is about 10^{14} cm, and so varied is the environment that material sometimes freezes into dust grains a thousand Ångstroms (10^{-5} cm) in size, and sometimes is completely ionized by the light of a nearby star. Local concentrations of ionized gas gave the first indication of the presence of interstellar gas because they radiate as emission nebulae in the visible spectrum when excited by a nearby hot star. Evidence of the presence of a more general distribution of gas came first from the study of spectra of distant, hot stars. These spectra contain peculiar, narrow absorption lines, which are not related to the stars but are superposed on the spectra by the intervening interstellar gas. The constituents observed are sodium, calcium, potassium, titanium, and iron, along with CH and CN—all absorption lines arising from the ground state. The following Table I of Herbig (1963) shows the observed interstellar constituents. Not included in the entries are the so-called diffuse bands which remain unidentified but are observed as interstellar features in stellar spectra. By far the most abundant element is neutral hydrogen, which produces no absorption lines in the visible spectrum. The use of the optical interstellar absorption lines to study the gas is handicapped by the low abundance of the ions, by the uncertainty in theoretical knowledge of the ionization equilibrium, and by the small number of stars in which the lines can be observed. The situation is rather like trying to investigate the composition and motions of the earth's atmosphere by looking only at aurorae and at the absorption lines superposed on the solar spectrum by, say, CO$_2$ and neon.

A great step forward in the study of the interstellar gas was made when van de Hulst (1945) predicted, and Ewen and Purcell (1951) observed, the 21 cm line of neutral hydrogen arising from hyperfine levels in the $n=1$ level. Thus, for the first time use was made of this most abundant element in the study of the interstellar medium. Further steps are currently being made in the search for molecular and atomic constituents in the radio frequency spectrum. OH radicals and excited hydrogen atoms have been detected. The observed transition in OH arises from Λ-doubling in the ground state at 18-cm wavelength, and those in the excited

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TABLE I. Sharp interstellar lines.

Å	Identification	Classification
3072.97	Ti II	$a^4F_{\frac{3}{2}}-z^4D^\circ_{\frac{1}{2}}$
3137.53	CH	$C\ ^2\Sigma^+-X\ ^2\Pi$, $R_2(1)$ of 0, 0
3143.15	CH	$C\ ^2\Sigma^+-X\ ^2\Pi$, $Q_2(1)+{}^QR_{12}(1)$ of 0, 0
3146.01	CH	$C\ ^2\Sigma^+-X\ ^2\Pi$, ${}^PQ_{12}(1)$ of 0, 0
3229.19	Ti II	$a^4F_{\frac{3}{2}}-z^4F^\circ_{5/2}$
3241.99	Ti II	$a^4F_{\frac{3}{2}}-z^4F^\circ_{\frac{3}{2}}$
3302.38	Na I	$3^2S_{\frac{1}{2}}-4^2P^\circ_{\frac{3}{2}}$
3302.99	Na I	$3^2S_{\frac{1}{2}}-4^2P^\circ_{\frac{1}{2}}$
3383.76	Ti II	$a^4F_{\frac{3}{2}}-z^4G^\circ_{5/2}$
3440.61	Fe I	$a^5D_4-z^5P^\circ_3$
3447.08	CH$^+$	$A\ ^1\Pi-X\ ^1\Sigma$, $R(0)$ of 4, 0
3579.02	CH$^+$	$A\ ^1\Pi-X\ ^1\Sigma$, $R(0)$ of 3, 0
3719.94	Fe I	$a^5D_4-z^5F^\circ_5$
3745.31	CH$^+$	$A\ ^1\Pi-X\ ^1\Sigma$, $R(0)$ of 2, 0
3859.91	Fe I	$a^5D_4-z^5D^\circ_4$
3874.00	CN	$B\ ^2\Sigma^+-X\ ^2\Sigma^+$, $R(1)$ of 0, 0
3874.61	CN	$B\ ^2\Sigma^+-X\ ^2\Sigma^+$, $R(0)$ of 0, 0
3875.76	CN	$B\ ^2\Sigma^+-X\ ^2\Sigma^+$, $P(1)$ of 0, 0
3878.77	CH	$B\ ^2\Sigma^--X\ ^2\Pi$, $R_2(1)$ of 0, 0
3886.41	CH	$B\ ^2\Sigma^--X\ ^2\Pi$, $Q_2(1)+{}^QR_{12}(1)$ of 0, 0
3890.21	CH	$B\ ^2\Sigma^--X\ ^2\Pi$, ${}^PQ_{12}(1)$ of 0, 0
3933.66	Ca II	$4^2S_{\frac{1}{2}}-4^2P^\circ_{\frac{3}{2}}$
3957.70	CH$^+$	$A\ ^1\Pi-X\ ^1\Sigma$, $R(0)$ of 1, 0
3968.47	Ca II	$4^2S_{\frac{1}{2}}-4^2P^\circ_{\frac{1}{2}}$
4226.73	Ca I	$4^1S-4^1P^\circ$
4232.54	CH$^+$	$A\ ^1\Pi-X\ ^1\Sigma$, $R(0)$ of 0, 0
4300.32	CH	$A\ ^2\Delta-X\ ^2\Pi$, $R_2(1)$ of 0, 0
5889.95	Na I	$3^2S_{\frac{1}{2}}-3^2P^\circ_{\frac{3}{2}}$
5895.92	Na I	$3^2S_{\frac{1}{2}}-3^2P^\circ_{\frac{1}{2}}$
7664.91	K I	$4^2S_{\frac{1}{2}}-4^2P^\circ_{\frac{3}{2}}$
7698.98	K I	$4^2S_{\frac{1}{2}}-4^2P^\circ_{\frac{1}{2}}$

hydrogen from high quantum jumps ($n>109$) at various centimeter wavelengths (Höglund and Mezger 1965; Lilley, Menzel, Penfield, Zuckerman 1966). The combination of information from the optical absorption and from the emission lines in both the optical and the radio-frequency regions should provide the means to attack both the problem of the distribution and of the behavior of matter in interstellar space.

In trying to review our present knowledge of this material which lies between the stars, we face the problem of limiting the subjects to be included. The problem arises not so much from the quantity of facts which are known as from the complexity and fascination of the currently unsolved problems. Our guide in the choice of problems to be included has been primarily a personal one—based on our own current interests and plans. This is, then, in no sense a complete digest of the whole problem of the interstellar medium; to attempt such a statement would be dangerous at a moment when the subject is in an explosive state of change.

We have included some description of the observational techniques available for studying the interstellar medium and where appropriate, a bit of the history of developments. The rapidity with which advances are being made in our understanding of the interstellar medium makes it essential to emphasize the transitory nature of any conclusions. This paper states very few such conclusions; it is full of statements of unsolved problems. Such a dynamic field is exciting to work in but difficult to describe coherently.

We begin with a general and largely qualitative description of what is known about the material which lies between the stars. The next section is one containing a brief description of the techniques available for observing the gas and dust, including their special applications and limitations. The remaining sections deal with the problems facing us in understanding the interstellar medium from the point of view of the physical conditions within it. Until recently the gas has been studied primarily as a tool for investigating the structure of our galaxy—at least in the radio-frequency portion of its spectrum. In particular, the hydrogen line has been used as a primary tool for investigating the large-scale kinematics of the galaxy and its spiral structure. Recently we have been able for the first time to study the nature of the gas itself as a major constituent of our environment (on an astronomical scale). We deal first, in Sec. II, with the velocity field of the gas, both in terms of motions of clouds and in terms of the motions within a single cloud. Section III is a description of the interstellar grains and the information they yield on the interstellar conditions. We then discuss, in Sec. IV, the deductions made about the galactic magnetic field from studies of the interstellar medium. The problem of the formation of molecules in the gas forms the subject of Sec. V. The last section, VI, deals with the very recent discoveries in the microwave spectrum of the interstellar gas.

With regard to references, we aim at making it possible to locate all original work on the subject by including in the bibliography primarily the review papers which will lead the reader back to the original papers. There are, of course, references to the original work directly, but they are by no means complete.

B. What's There

The interstellar medium consists of all matter which is not contained in the stars. In this section we present a brief description of the gaseous constituents of the medium. The detailed study of the majority of the kinds of objects has been made in the Milky Way; moreover, examination of the nearby galaxies (primarily the Magellanic Clouds and M31 and M33) shows evidence for the same types of interstellar objects.

As we have pointed out, a relatively large percentage of the mass of the Milky Way is contributed by the interstellar gas. Our galaxy consists of spiral arms similar to those in the nearly spiral galaxies such as the Andromeda Nebula (M31). The Galaxy (Milky Way) has a diameter of about 30 kparsecs (1 parsec$=3\times10^{18}$ cm) and a relatively small thickness; thus, the over-all form is that of flattened disk. The sun is located 10 kparsecs from the galactic center, where the interstellar gas has a total thickness which is about 200 parsecs.

Emission nebulae and reflection nebulae are very prominent regions in the interstellar medium. The emission nebulae are regions of high excitation (kinetic temperatures of $\sim10^4$ °K) surrounding hot, luminous stars (O stars); the nebular spectra consist of the recombination lines of hydrogen and other elements, and the forbidden lines of oxygen, sulfur, and nitrogen, which are excited by electron collision. Further observations of hydrogen in the emission nebulae are now possible using the high quantum number "jumps" whose frequencies lie in the microwave spectrum.

The emission nebulae are of great importance for abundance determinations in the interstellar gas. The high excitation produces numerous lines of various elements, thus providing an opportunity for a fairly complete abundance analysis. These results indicate that the abundances of the elements in the interstellar medium are quite similar to those found in stellar atmospheres.

The reflection nebulae are regions of nebulosity with a continuous spectrum surrounding cooler stars (type B1 and cooler). As we will point out in Sec. III, this nebulosity is due to scattered light from interstellar dust grains in the vicinity of the star. It appears that the type of nebulosity depends not on the type of interstellar material (either gas or dust) but on the temperature of the exciting star. The consensus is that the composition of the clouds in the case of the two types of nebulae is the same; the interstellar matter accommodates itself to the radiation field near the star.

As we will show in Sec. IIA, most of the interstellar gas seems to be concentrated in discrete clouds of sizes 2–6 parsecs which occupy 10% of the volume in the galactic plane. Strömgren (1939, 1948) has shown that the interstellar gas is divided into two types of regions: HI (neutral hydrogen) and HII (ionized hydrogen) regions. The latter are the emission nebulae surrounding hot, luminous stars. This distinction is made for hydrogen since this element is by far the most abundant gas in the interstellar medium.

The HI regions have a kinetic temperature of $\sim$125°K (see Sec. IIB), while the HII regions are characterized by kinetic temperatures of $\sim10^4$ °K. The HII regions contain only a small fraction (about 10% in a spiral arm) of the interstellar gas, due to the fact that the O stars are relatively rare. The interesting property of the HII regions is the sharp transition between them and the surrounding neutral gas. Near the exciting star practically all the hydrogen is ionized (HII)—the density of HI being about 10^{-2} times the density of HII. As the distance r from the star increases, the energy density beyond the Lyman limit falls off as r^2; more important, the opacity due to HI between r and the star increases exponentially ($\propto e^{-\tau}$, where τ is optical depth at Lyman limit 912 Å) as the number of neutrals increases. Using the Saha ionization equation with the above two effects included, Strömgren showed that the feedback between the two effects causes a very sharp transition region between HI and HII. The radius of the so-called "Strömgren sphere" is given by

$$r_0=R_0 n_{\mathrm{H}}^{-\frac{2}{3}},$$

where n_{H} is the total number density of H atoms and R_0 equals $(3L/4\pi\alpha)^{\frac{1}{3}}$, where L is the luminosity of the star and α is the recombination coefficient. Within r_0 practically all the hydrogen is HII; for $r>r_0$, the hydrogen is almost completely HI. For $n_{\mathrm{H}}=10$ cm^{-3}, $r_0=30$ parsecs for an O5 star; for a cooler B5 star $r_0=0.8$ parsec. For stars as cool as the sun, $r_0\approx10^{-4}$ parsec. Thus, only for stars hotter than B0 are the emission nebulae prevalent objects.

As a consequence of the "Strömgren spheres" the radiation field in HI regions has a sharp cut-off at the Lyman limit—the photons of higher energy are absorbed in the HII regions. A knowledge of the spectrum of the interstellar radiation field is important in two respects: (1) The calculation of the ionization equilibrium in the interstellar medium requires the shape of the interstellar radiation field at and beyond certain ionization limits. The ionization equilibrium is needed to calculate the total abundance of a particular nuclear species from the observed concentrations of one of its ions, e.g., we observe Na^0 in the interstellar medium; since most of the sodium present is Na^+, we must use the ionization equation to calculate the interstellar sodium abundance. (2) As we point out in Sec. V, molecular formation in the interstellar medium depends critically on the radiation field. Various authors (Dunham, 1939; Lambrecht and Zimmerman, 1955; Stecher and Milligan, 1962; and Zimmerman, 1965) have attempted to calculate the interstellar radiation field using the observed numbers of different types of stars. This calculation is extremely difficult due to our lack of knowledge of stellar radiation below the earth's atmospheric cut-off at 3000 A. Furthermore, a correction must be made for the ultraviolet interstellar extinction (see Sec. IIIB)—again unobservable from the earth's surface. The early estimates (Dunham, and Lambrecht and Zimmerman) approximated the stellar radiation in the ultraviolet by a blackbody approximation, while the later calculations by Lambrecht and Zimmerman have utilized model atmospheres to calculate the ultraviolet contributions of the stars. The Stecher and Milligan calculation is based on observations of the stars in the region 2600–1600 Å by rockets; these observations indicated that the model atmospheres had grossly overestimated the ultraviolet contributions. The Zimmerman (1964) calculation utilizes improved model atmospheres.

Figure 1 illustrates the comparison between the five calculated radiation fields in the region 3800 Å to the Lyman limit at 912 Å. If the Stecher and Milligan field is correct, the ionization of those elements whose ionization energies lie in the region 5–13 eV would be greatly reduced. The great disparity between the recent calculations is indeed discouraging. Nevertheless, it is obvious that the interstellar radiation field leads to great deviations from thermodynamic equilibrium.

In the interstellar medium, many of the objects which appear as major structural features are regions of exceptional states of excitation or regions of unusual interaction with certain types of stars. These features contain a very small percentage of the mass of the interstellar medium. They are important, however, since they exhibit various degrees of excitation, densities, and ages. The quasi-attached shells and envelopes of certain objects such as novae, emission stars, and planetary nebulae are examples of these types of features. The supernovae and their remnants (the explosion of certain types of stars and the interaction with the interstellar gas) are of great importance because of the vast amount of energy involved in these events. In Sec. IIC, we mention the possible importance of supernovae as energy sources for the whole interstellar medium.

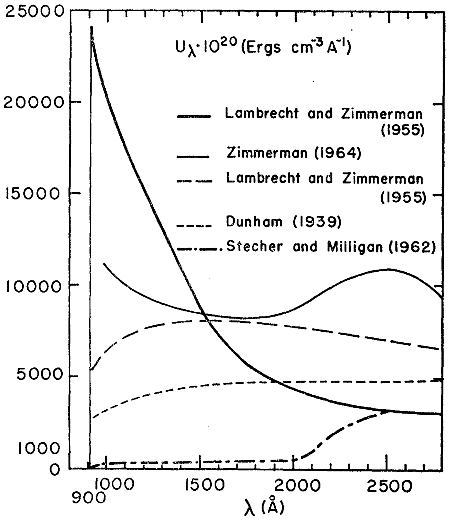

Fig. 1. The interstellar ultraviolet radiation field in H I regions according to various authors (Stecher and Milligan 1962). The Lyman continuum cut-off at 912 Å is indicated. The solid line curve for L–Z refers to model atmospheres for the stars and the dashed line for L–Z refers to a blackbody approximation for the atmospheres.

C. Observational Techniques

We wish now to describe the techniques used to study the interstellar medium. They may be classified by the wavelength range studied, that is, into optical and radio-frequency approaches. Each approach deals in its own way with the absorption by the interstellar medium of the continuous radiation from distant sources—in the optical case from starlight and in the radio case from radio sources. Each approach also deals with the emission of the interstellar gas itself, the visible emission arising only from excited regions of the galactic gas, the microwave emission originating throughout the galaxy in the case of neutral hydrogen and from excited regions in the case of OH.

The presence of an absorbing material in interstellar space is apparent from photographs of the Milky Way. This material absorbs the light of distant stars in a way dependent on wavelength, and it polarizes the light which penetrates it. These observations provide important clues to the nature of this interstellar dust.

Observations of the interstellar gas by means of its selective absorption of the light of distant stars was, until 1951, the only way this component of the diffuse, pervading material could be detected. It was found that the spectra of some hot stars showed very sharp absorption lines of atoms and molecules quite uncharacteristic of the rest of the spectrum. The observation that they did not share the stellar motion, especially in the case of double stars, established that they originated in the space between the observer and the star. In many cases it was found that the lines had several closely spaced components, presumably Doppler-shifted with respect to one another, and this led to a model of a gaseous medium made up of individual clouds. This model consisted of about 10 such clouds per kiloparsec along the line of sight.

The study of these lines faces many difficulties—some inherent in nature and others imposed by instrumental limitations. In the former category is the fact that the gas is so diffuse that very long light paths are required to produce a measurable absorption line in a stellar spectrum. The star must, therefore, be at a great distance—and is consequently rather faint. The stars which might be useful are often reduced in brightness not only by the distance effect but also by the interstellar extinction which occurs in directions likely also to contain the gas. These factors have limited the maximum distance of stars in whose spectra are observed interstellar lines to about 2.5 kparsecs (about 8×10^{21} cm), and thus, on the average, the distance of the observed interstellar gas to about one-half this distance. This restriction on the region of the galaxy which we can study by this technique is a severe one when one remembers that the center of the galaxy is 10 kparsecs away from the sun. Another natural difficulty arises from the fact that in order to detect an interstellar line, measure its wavelength (and hence radial velocity), and intensity one must find it in a stellar spectrum which does not have strong stellar lines of the interstellar atoms sought for—usually Na° and Ca^+. This means we need to study "early-type" stars—young, hot, massive stars, which are much rarer than the cooler ones. This further restricts the observational material—especially if one wishes to look at regions out of the plane of the galaxy, where young, hot stars are rare.

Measurement of the precise wavelength of an interstellar line is hampered by the difficulty of obtaining the spectra at high dispersion. The faintness of the stars requires the average spectrum to be taken with a 5-h exposure with a 100-in. telescope, for example. Consequently, the accumulation of data is limited by the observing time available on large telescopes. The use of image tubes to increase the sensitivity of such instruments (by an order of magnitude) may well soon make possible a great increase in the amount of data. With spectra now available obtained with conventional techniques, errors in wavelength measures and hence, in radial velocity estimates, are likely to be 1 to 3 km/sec. This is far less accuracy than can be attained easily by radio-frequency techniques. With two new and sophisticated techniques higher resolution has been obtained: use of a high resolution solar telescope on stars by Livingston and Lynds (1964) gives velocities within $\frac{1}{2}$ km/sec, and use of a Fabry–Perot interferometer by Hobbs (1965) gives them to within $\frac{1}{4}$ km/sec. Both techniques are difficult and are limited to use with bright objects, but they do equal the highest radio-frequency resolution now routinely available.

In terms of detection of a small concentration of an element, however, the optical techniques far out-do the radio ones. This is primarily due to the higher transition probabilities in the spectral lines studied. A typical optical line is formed by about 3×10^{11} atoms/cm^2 along the line of sight, while the weakest observed neutral hydrogen (1420 Mc/sec) lines are formed by of the order of 10^{19} atoms/cm^2. Actually, nature works for us in this case, because the hydrogen is so abundant compared to the sodium and calcium (by a factor of 10^6) that a high transition probability in this radio-frequency transition would mean we would reach high optical depths for a small length of absorbing gas, and thus be unable to observe the gas far away. So, if we could choose, this combination of circumstances would be our choice. (In this regard molecules provide an intermediate case; that is, the detection possibility for a given number of molecules is about the same in the two spectral regions.) Interpretation of the optical results in terms of the abundance of calcium and sodium is, however, hampered by a peculiar circumstance. In the visible spectrum the lines of Ca^+ and Na° are those observable, but in the interstellar medium most calcium is in the form of Ca^{++} and most sodium is Na^+. What is required, then, is a knowledge of the ionization equilibrium in interstellar space, which depends on the atomic ionization cross sections and the radiation field, neither of which is well known, as we pointed out in Part B of the introduction.

Optical observations suffer from one further natural limitation which will soon be overcome by the newest instrumental advances. The limitation is that the earth's atmosphere cuts off the radiation below 3000 Å and above 20 000 Å. The advance is, of course, the instrumented satellite. The primary contribution of the satellite observations to the problem will be the extension of our knowledge of the spectrum of the interstellar gas both into the ultraviolet and the far infrared. In the ultraviolet lie strong lines of abundant atoms like carbon, nitrogen, oxygen, and iron. In addition, from these lines we get a far clearer picture of the composition of the gas and possibly a measure of the ionization equilibrium and electron density. A particularly important advance may be made because the hydrogen molecule produces bands in both the ultraviolet and infrared. This molecule could well be a major constituent of the interstellar gas which has until now completely escaped detection. A full discussion of the possibilities of observations in the ultraviolet has been made by Spitzer and Zabriskie (1959).

All these optical methods suffer a serious limitation compared to some radio-frequency ones and in turn have an important advantage over them. The limitation is that all the measurements depend on the presence of a star as a background source of radiation. This prevents a mapping of the sky on an extensive and detailed scale and limits our understanding of the structure and dynamics of the gas derived in this way. The advantage is that an upper limit to the distance of the intervening material is available from the distance of the star. In only a few cases is such an estimate available in the studies of the microwave spectra of the gas—the most notable case being the OH emission from bright, diffuse nebulae. The velocity of the hydrogen emission has been used to estimate its distance, but this depends on the adoption of an uncertain model for the rotation of the galaxy.

Observations of the interstellar medium by radio-frequency techniques has its own set of problems and potentialities. The very large difference in wavelength from the visible radiation (of the order of 10^6) leads to greatly different observational methods. For example, the angular resolution of the largest radio telescope used in studies of interstellar microwave lines is about 10 min of arc, a far cry from the seconds of arc obtainable optically. On the other hand, the frequency resolution of a radio astronomy receiver can easily be a few kilocycles/sec—equivalent to less than half a kilometer/sec in terms of Doppler shifts, while the optical resolution is usually not greater than 1 km/sec. The technique in optical spectroscopy is to photograph the spectrum of a star (covering the whole visible range) and to search in it for lines of interstellar gas of known atoms and molecules. This is, if not impractical, at least much more difficult in the radio-frequency range. An observation there covers at most a small fraction of the spectrum, of the order of 10^{-3} times the average frequency of the line. It has therefore been possible to study only one interstellar constituent at a time, with a consequent cry from observers for better values of the frequencies of lines to be expected from materials in the interstellar gas.

One aspect of radio observations of the interstellar gas is similar to optical observations. This is the technique of observing the absorption lines superposed on spectra of distant sources by the intervening gas. The situation is in some ways better and in some ways worse than in the optical case. On the positive side, the radio sources are not dimmed by interstellar dust and so in a few cases permit observations over very long path lengths. In addition, the sources have no observable intrinsic spectral lines to complicate the measurement of the interstellar ones. However, only a handful are bright enough to permit observation of absorption lines of even the strongest microwave line—the 1420-Mc/sec line of neutral hydrogen. A further problem arises from the low angular resolution of the antennas. An observation in the direction of a source includes also radiation from a considerable solid angle around the source. Only clouds in the line of sight between observer and source will absorb radiation from the source, but all other lines of sight within the solid angle will contribute to the measured profile. They will in general add emission to the profile at about the absorption line frequencies and hence weaken the apparent absorption. Study of the absorbing clouds therefore requires that the contribution of emitting regions be removed by constructing what this emission would look like in the absence of a radio source. The usual procedure involves an interpolation between nearby regions, and contributes significantly to the uncertainties in measurement of intensities of the lines. Nevertheless, the observation of absorption lines makes possible a large increase in effective angular resolution since the principal factor is no longer the beam width but the angular size of the source.

Observation of the microwave line at 1420 Mc/sec of neutral atomic hydrogen in the interstellar medium has special advantages over any other available technique for studying the gas. In the first place, hydrogen is by far the most abundant element in the gas. The properties of the transition are very accurately known—the frequency, transition probability, and excitation mechanism. Recent work on other microwave lines originating in the interstellar medium has shown the importance of these factors; for example, the uncertainty in the excitation mechanism for OH is a real problem. In the case of the HI hyperfine transition, however, the excitation is known to be collisional and the brightness temperature[1] of an optically thick cloud therefore represents the kinetic temperature of the gas. In addition the kinetic temperature derived from the thermal Doppler broadening of observed lines is a direct measure of the excitation temperature, if there is no turbulence.

Absorption measurements offer a way of detecting weaker HI lines than is possible in emission. For an individual interstellar cloud lying in the same line of sight as a radio source, the brightness temperature

$$T_B = T_L - T_C,$$

where T_L is the brightness temperature in the spectral line, and T_C is the brightness temperature of the continuous source. Integration of the equation of transfer along the line of sight gives

$$T_L = T_C e^{-\tau} + T_{\mathrm{ex}}(1 - e^{-\tau}),$$

where T_{ex} is the excitation temperature of the gas, and

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[1] In the radio spectrum intensities are measured in terms of a brightness temperature. This follows from the Rayleigh–Jeans approximation to the Planck function:

$$B = (2kT\nu^2/c^2) \text{ (ergs/sec cm}^2\text{ cpc sr)}.$$

Hence, all intensities can be expressed in terms of an equivalent brightness temperature.

τ is its optical depth. The equation for the brightness temperature is then

$$T_B = -T_C(1-e^{-\tau}) + T_{\text{ex}}(1-e^{-\tau}).$$

When $T_{\text{ex}} < T_C$, we observe an absorption line; when $T_C < T_{\text{ex}}$, we observe an emission line. The brightness temperature of many sources is much greater than the excitation temperature of the interstellar hydrogen, and these sources offer the possibility of observing clouds with very small optical depths.

The second advantage in observing the hydrogen line is that it is detectable in emission over the whole sky. An observer is not limited to directions containing background sources and can therefore map the distribution of the gas over the sky. He has then a three-dimensional view of the interstellar gas, two dimensions on the celestial sphere and one in the frequency or velocity domain because of Doppler shifts of the observed lines. In one case—that of observations made in the galactic plane—this third dimension can be converted into distance. Here the dominant radial velocity shifts are due to differential galactic rotation and can be related to distance from the galactic center through the assumption of a model of this rotation. In other directions, however, there is no estimate possible of the distance of the emitting material without observations made in some other way.

This problem suggests the importance of the combination of radio and optical techniques. If, for example, a cloud of interstellar gas can be observed both in the microwave radiation from its hydrogen atoms and in the optical radiation of others of its constituents, the first dividend is an upper limit on the distance of the cloud (the distance of the star). This, in combination with the angular size of the cloud, yields the linear size and hence the density and mass of the cloud. Another piece of valuable information derivable from the combined observation is the abundance of the trace elements in the gas in relation to the hydrogen. Another area in which the combined optical and radio techniques should yield large dividends in our understanding lies in the study of the HII regions, the diffuse nebulae. Observations of the emission of the OH molecule from these clouds and the optical radiation from the other elements present will surely open new avenues for understanding the complex mechanisms operating in these excited regions. Further progress in the development of each of the techniques will soon make possible significant progress in many areas of study of the interstellar medium.

II. THE VELOCITY FIELD

A. Cloud Structure and Velocities

We shall now discuss the kinds of specific information about this interstellar medium which we can deduce from use of the various techniques—to begin with, the nature and velocities of interstellar gas clouds. The stars in our galaxy move quite independently of one another, each under the influence of the force field of the galaxy, but each affected in only a minor way by nearby stars. The gas between the stars, however, interacts significantly with nearby material so that it can be said to have a definable pressure, density, and temperature at each point. The investigation of these thermodynamic quantities is intimately tied to studies of the velocity fields in the gas, which can be made, to a limited extent, with present techniques.

We can measure the position in space, central wavelength, and frequency profile of a spectral line—absorption or emission—which we identify as coming from the interstellar gas. The measure of the wavelength gives us two things: an identification of the constituent producing the line; and a measure of the velocity of the "object" along the line-of-sight. The profile of the line measures for us two kinds of things: the dispersion in velocity along the line-of-sight of all the infinitestimal elements of gas producing the line; and the number of atoms along the line-of-sight. With respect to the interstellar medium, there is usually little ambiguity in the interpretation of the wavelength measures. In studying the optical spectra, it was noticed very early that the spectral lines coming from a single element were often split into several components, whose widths were small compared with their separations. Such a result suggested the presence of condensations of matter, moving with differing velocities. The number of these components was found to increase in number with the distance from the sun to the star in whose spectrum the interstellar line was observed. Thus the suggestion arose that the interstellar medium actually consists of "clouds", rather than of a homogeneous layer. These clouds occupy only about 10% of the total volume, and their densities are several orders of magnitude greater than the surrounding medium. Presumably, if there were indeed a substratum in which there were differential velocity fields, the various components of the spectral lines would not be so clearly separated, but would blend more. So this picture of an interstellar medium concentrated into clouds, with any residual substratum being only a small fraction of the whole, has gained acceptance. (For a review of the subject, see Spitzer, 1966.)

More recent observations have supported the model and have led to a more quantitative description of a typical cloud. The great observational difficulty has been to be certain that one is looking at the velocity profile of a single cloud and not a blend of many clouds along the line of sight. One piece of evidence that earlier data on clouds was distorted by this effect comes from an examination of the interstellar lines in the bright star α Cygni. Adams (1949), with a resolution of 8 to 16 km/sec, found two components in the interstellar calcium lines in the spectrum of this star. In 1964, Livingston and Lynds, using a solar telescope with a resolution of 0.5 km/sec, found five components in the same lines. Application of radio techniques to the problem of cloud structure was made by means of a survey with high-frequency resolution (2 kc/sec or 0.4 km/sec) in the 21-cm hydrogen line in the area around the north galactic pole (Dieter, 1965). In this direction we are observing along the shortest path length in the interstellar medium where we might expect to see clouds separately. Four clouds are, in fact, individually observable in this area. On the reasonable assumption that the clouds are about 100 pc away, the average diameter is 10 pc; the average density, 2 atoms/cc; and the average mass, 15 solar masses. The diameter is similar to that deduced from more indirect evidence, but the densities and masses are both lower than previously found.

A typical cloud will have within it a small quantity (1/100 of the gas by weight) of grains. The observations which support this statement are not entirely unambiguous, but do suggest it to be true on the average. The radii and number density of the gas clouds and the dust clouds are found to be the same, although they are observed by quite different techniques. Interstellar extinction is high in directions in which the Ca^+ absorption is large, and on a large scale it correlates also with the neutral hydrogen emission. Attempts to derive the gas-to-dust ratio as a constant throughout the interstellar medium have, however, not proved successful when they have dealt in detail with small volumes of space.

This picture of the interstellar gas existing in the form of discrete clouds is, however, not without difficulty. In the first place we do not know what maintains the cloud as a unit. A typical cloud would not be held together by self-gravitation, but would dissipate into the intercloud medium in a time of the order of 10^7 years—a time short compared to the age of the galaxy. Either clouds are continually being formed or something holds them together.

Two proposals have been made for the nature of an external pressure acting to stabilize these interstellar clouds (in addition to a controversial magnetic pressure). Although each is plausible, neither is susceptible to an obvious quantitative test. The first, due to Spitzer (1954), depends on the balance of pressure between the cloud and intercloud material. He proposes that the clouds are cool, relatively dense condensations in a hot, very tenuous medium. The pressure within a cloud, which is proportional to the product of its density and temperature, is balanced by that of the intercloud gas where the temperature is high ($\sim 10^6$ °K) and the density low. The density is so low that the intercloud gas is essentially unobservable. The second suggestion for the source of the external pressure, due to Kahn (1955a), is the collision of the cloud with other clouds. Such cloud–cloud collisions will be mentioned as a means of limiting grain size (Sec. III) and discussed as a means of heating the interstellar gas. Here an average cloud is described as having a mean free collision time of 10^7 years. A collision compresses the cloud and the pressure resulting from such collisions depends on the random cloud motions. Both the specific details of the compression mechanism and the parameters which govern it are poorly understood. Thus, we can only accept that the clouds exist and speculate on their persistence.

In order to discuss the velocity fields associated with these clouds we shall describe the hierarchy of motions, as we think we understand them. When we measure the radial velocity of a component in the profile of an interstellar absorption or emission line, we can identify it with various motions of the gas. In general, the measured velocity is affected by

(a) differential galactic rotation on the basis of circular orbits,

(b) systematic group motion of many clouds deviating from circular orbits,

(c) random motions of individual clouds in the group.

Two further velocity fields affect the line by broadening it—gas streaming in one cloud and thermal motions of individual atoms in the cloud. By gas streaming, we mean mass motions within the cloud which are not dependent on the mass of particles within it. It is useful to make this arrangement of effects because we want to understand the details of the rotation of the galaxy, to find the forces which drive the additional systematic motions, and to calculate the dissipation of energy, partly due to the collisions of individual clouds. We have, however, two problems in making and using the arrangement. One is a conceptual one, in that we cannot really justify treating an "individual cloud" like a self-contained unit if we first give it motion in common with other such units and then say it has streaming motion within itself. We are not sure what is a cloud and what is not. So, conceptually, the arrangement has flaws. The second problem is that it is not possible, except in unusual cases, to observe the effects separately. We measure, after all, a single radial velocity for a component of interstellar absorption or emission. This velocity is affected more or less by all these motions. We can make a reasonable attempt to separate the differential galactic rotation contribution to the radial velocity because we understand the rotation fairly well. The galaxy rotates as a whole—stars and gas together—in such a way that the velocity increases roughly linearly with distance from the center, up to just short of the sun's distance. Beyond that it rotates in a way which is thought to approach a Keplerian form. We cannot, however, distinguish in general between systematic motions of groups of clouds and individual cloud random motions within the group. This probably does not affect our interpretation of the group motions very much, but it does affect in a devastating way our interpretation of random cloud velocities, because they are not truly random but partially systematic.

The conceptual problem does not seem susceptible to solution at the moment. The observational problem holds out greater hope because of the increasing precision of 21-cm hydrogen emission line measurements.

These measurements have given us some insight into the systematic group motions, although explanations only for those in the galactic plane. Surveys of the neutral hydrogen emission in the plane have indicated the structure of the galactic system, including the spiral arms, and have delineated the rotation of the system, an example of the group (a) motions. Surveys of neutral hydrogen emission out of the plane (McGee and Murray, 1961; McGee, Murray, and Milton, 1963; Dieter, 1964–5) have shown that there is great asymmetry in these motions in the sense that most of the material is approaching the sun, an example of group (b) motions. What is more, there are large-scale features observable in this approaching gas, especially at high galactic latitudes. (Galactic latitudes are measured with the sun as center and the galactic plane as zero point.) On the average, if one observes at high latitudes one is seeing gas closer to the sun than at low latitudes, because the layer of gas is highly flattened. The survey by Oort, Blaauw, Hulsbosch, Muller, Raimond, and Tolbert (1966) covers with a coarse grid of observations the area of the sky from 40° to the north galactic pole. There is at all positions some gas nearly at rest with respect to the region about the sun, but all departures from this quiescent gas are in the negative velocity sense. In particular, over about half the total longitude range there is more of this approaching gas than there is gas at rest. The highest velocities and greatest densities occur at all latitudes at about a longitude of 120°, and near this same longitude there is very little zero velocity material. (Longitude is measured with the sun as center and the galactic center as zero point.) These authors suggest that the explanation may lie in a flow of gas which has disturbed the quiescent hydrogen layer near the sun. Results of a similar survey by van Woerden, Takakubo, and Braes (1962) at intermediate latitudes (15° to 40°) show an excess of negative velocity components also centered at a longitude of 120°, suggesting that the flow extends over a very large volume near the sun.

A natural question which arises is—just how much material is involved in such a local disturbance? It is one which is impossible to answer directly except in special cases, because we do not normally know the distance to the emitting HI. We therefore have no measure of the volume of the gas and hence no way to translate our measure of the number of hydrogen atoms per cm^2 along the line of sight to a total mass of material. It is clear, however, that this "disturbance" contains a significant fraction of the interstellar gas near the sun at these latitudes.

A more detailed survey near the galactic poles (Dieter, 1964) shows another case of a large-scale systematic motion of a group of clouds. Near the poles, looking directly out of the galactic plane at the sun's distance from the center, one observes the shortest path length through the interstellar gas and one along which differential galactic rotation should have no effect (since the local gas shares the same rotational velocity). In neither polar cap does the expected simple velocity picture appear; there is again gas approaching the sun. In the case of the polar observations, one is observing as radial velocity the true velocity of the gas with respect to the galactic plane. At other latitudes one is unable to determine how much of the observed radial velocity is attributable to this so-called z-motion. In both polar caps there is some gas at rest and some approaching the plane with rather high velocities. In the north the two components are clearly separable—one near zero velocity and the other with velocities ranging from -20 to -55 km/sec. The approaching gas shows a very complex pattern of velocities with no apparent systematic effects. Areas over which similar velocities appear are several degrees in extent, suggesting that the gas is relatively nearby. In the case of the polar observations one can make a somewhat more quantitative estimate of the distance from the fact that the layer of gas around the galactic plane is known to have a total thickness of about 200 pc. If one assumes that the zero velocity and the negative velocity gas exist at the same mean distance from the sun, the approaching gas contains 0.4 of the total amount of hydrogen in the region. If this distance is 100 pc, this gas has a mass 400 times the mass of the sun. A larger assumed distance for this component will increase both its percentage and its mass. If one now assumes that at the sun we are observing a flux of material approaching the plane which is typical of the whole galaxy, we can calculate how much material is "falling in" to the plane from both north and south. This assumption has very little validity since we have only a small sample area—10^{-5} times the total—and we know that conditions near the center are markedly different from those in the solar neighborhood. As an indication only, then, this assumption leads to the conclusion that 100 solar masses reach the galactic plane each year.

One naturally asks where all this material comes from. One logical assumption is that it is part of a large-scale flow of material from one part of the galaxy to another, perhaps up out of the center and down onto the plane farther out. The absence of any observed positive velocities requires either that the flow is oriented so that none of the gas is receding from us or that this gas is unobservable—low density, ionized hydrogen, for example. All this is believable enough but can scarcely be said to be based on anything but conjecture. Two possibilities are that this is a continuing, normal flow of interstellar gas occurring throughout the lifetime of the galaxy or is a result of a catastrophic event (perhaps at the nucleus of the galaxy), which occurs over a period short compared to the lifetime of the system.

In optical observations of interstellar absorption lines at positions all over the sky, components of rather high velocity are found, and a large percentage of them are approaching the sun. A survey of interstellar lines in the spectra of stars high above the plane by Münch and Zirin (1961) shows, in fact, that 32 out of 46 components have negative radial velocities, and hence a component in the direction of the galactic plane. Comparison of these high velocity clouds with the low velocity ones turns up a curious difference in the abundance of elements within them. The two principal lines measured are those of neutral sodium and singly ionized calcium. In the low velocity clouds the ratio of calcium to sodium atoms is lower than that in the high velocity clouds by a factor of about 6. Implicit in the determination of the relative abundance is the calculation of the ionization equilibrium of each of the elements, which depends on the radiation field in which the material finds itself. The most likely supposition is that the radiation field is different on the average in the low and high velocity clouds. This is, however, only supposition and mainly serves to throw doubt on our calculations of all abundances in the interstellar gas. An ingenious explanation due to Spitzer (1954) is that the high velocity clouds have recently been accelerated by being in the neighborhood of a bright, hot star. The high radiation field near the star may also have served to evaporate more calcium atoms from interstellar grains (described in Sec. III) and hence leave more in the gaseous state.

A somewhat rarer phenomenon, but one fully as difficult to explain, is the group of so-called "high velocity clouds" found first by Oort, Blaauw, Hulsbosch, Muller, Raimond, and Tolbert (1966). These are condensations of neutral hydrogen with very large radial velocities, from 60 to 175 km/sec, and all negative in sign. They have so far been found in two general areas, one between 70° and 165° longitude and between +15° and +50° latitude (where there are 11 clouds or agglomerations of clouds) and in the south galactic polar cap (where there are 3 or 4). In both areas it is apparent that the clouds are several degrees in angular extent and that they have a complex structure. It is very difficult to say anything about the nature of the clouds beyond this, because we have no idea at all of their distance. Our observations tell us only the number of atoms along the line of sight (between 10^{19} and $10^{20}/\text{cm}^2$) and the dispersion in velocity, 10 to 15 km/sec, which is rather high. Any further deductions depend on the distance—and we do not even know whether the objects are inside our galaxy or beyond it.

We should like to know also the velocities of individual clouds within a group, in particular, the form of the random velocity distribution of the clouds, in other words, motions described as group (c). The problem was first of interest in order to aid in estimating the number of clouds along the line of sight, in the face of incomplete velocity resolution of individual clouds. Different authors have used the form proposed by Blaauw (1952),

$$\exp(-|v|/\eta),$$

v being the mean speed of the clouds, and have derived values of η from their own observations. Results have ranged from 2 to 8 km/sec, depending on methods and places in the galaxy observed. The situation is hopelessly complicated by the presence of the large-scale systematic motions of groups of clouds already described. There are great differences in the form of the velocity distribution of the clouds at different places, which quite mask any "average" random motions. Blaauw's treatment of Adams' (1949) observations of optical interstellar lines in the galactic plane certainly shows a distribution of the exponential form indicated with $\eta = 2$ km/sec. More general surveys at both poles, however, indicated a very much flatter distribution with a large excess of high velocities (one quarter of the total are greater than 24 km/sec). In Münch and Zirin's (1961) optical study at high latitudes a very similar distribution is found, including the percentage of components above 24 km/sec. The procedure of treating only the absolute value of the velocity of course masks the fact of the great asymmetry toward negative values. Thus, a single function with a single determining parameter does not describe the observed cloud motions. One might hope that knowledge of such a function would provide an estimate of the energy in the form of individual cloud motions and hence a boundary condition on the choice of mechanism for the acceleration of clouds. It appears, however, that so many large-scale, unexplained motions of groups of clouds are present that we cannot find a clear description of the random ones within the groups.

B. Internal Motions in Interstellar Clouds

We turn now to the velocity fields which broaden the line profile produced by an interstellar cloud—gas streaming within the cloud and thermal motions. One of the central problems is to separate these two effects so as to deduce the amount of mass motion within a cloud and the kinetic temperature of the material within it. In the case of the 21-cm neutral hydrogen radiation, the kinetic temperature is also the excitation temperature because the excitation of the line is collisional (Purcell and Field, 1956). This is the case because the natural lifetime of the atoms in the upper level of this hyperfine transition is extremely long (about 10^6 years—this is due to the magnetic dipole character of the hyperfine transition). This time is long compared with the rate of collisions of the atoms, so that these collisions determine the populations of the atomic levels. In addition to its importance from this point of view there is the fact that this kinetic temperature depends on the balance of heating and cooling mechanisms in the interstellar gas and therefore its observed value provides a limit on requirements for these mechanisms.

An estimate of T_K for the neutral hydrogen has also been made on the basis of other considerations than line broadening. The estimate is based on the difference in brightness temperature along paths of different lengths in the galactic plane. The accepted value from this technique is 125°K, but this is only an upper limit because the measured brightness temperature is actually the harmonic mean of the temperatures of all the clouds along the line of sight (Kahn, 1955a). This means that the clouds with lower temperatures are weighted more heavily in this average, and the value derived is therefore not even a proper upper limit for the temperature in a single cloud. The most direct way to derive the kinetic temperature of the interstellar gas is to measure the dispersion in velocity of a spectral line produced by a single cloud. There are two problems in doing so; one is to eliminate the contribution to the broadening of the line by gas streaming in the cloud, and the other is to observe the profile from a single cloud, not a superposition of many along the line of sight. We shall discuss the first problem later in this section. No solution to the second problem is possible with presently existing radio telescopes when one is looking at neutral hydrogen emission along the galactic plane. The blending of radiation from the many clouds along the line of sight is too severe to be resolved by even very high-frequency resolution techniques. The greater angular resolution available by use of the absorption features in the spectra of continuum sources mitigates the problem somewhat, but one is still not quite sure that any feature in the spectrum is indeed a single cloud. Another possibility for observing single clouds along the line of sight is that of looking at high galactic latitudes where the path length through the dense gas in the plane is small. In this case one can in some places isolate individual clouds.

Two surveys of hydrogen emission have been carried out at positions out of the galactic plane, one at intermediate latitudes (van Woerden, Takakubo, and Braes, 1962; Takakubo and van Woerden, 1966) and one near the north galactic pole by Dieter (1965). Each of the surveys was carried out with rather low angular resolution but with very high resolution in velocity, equivalent to 0.4 km/sec in the intermediate latitude survey and 0.2 km/sec in the polar one. The results of the velocity dispersions measured can in no way be considered representative, since profiles which appeared to have narrow features were chosen for study with the high resolution. In fact, the higher velocity components in the profiles were not included since they, in general, have larger dispersions. The principal object of these studies was to find the narrowest possible components—those which were most likely not be blends. The dispersion of such a narrow component would of course still not be a direct measure of the temperature because of the possible presence of gas streaming in the cloud, but would be an upper limit to the temperature in that cloud. The hope was to find some which were narrower than the Doppler width corresponding to a temperature of 125 °K and hence evidence for cooler clouds. This dispersion is 1.0 km/sec for HI. No such clouds were found. The median dispersion in the polar survey was 2.5 km/sec, and the intermediate latitude values were similar. More significant is the fact that the narrowest line observed in each survey was 1.1 km/sec wide, even though the instrumental broadening was far below this level.

One may also use the technique of absorption measurements in the hydrogen line to measure dispersions. The primary advantage in this technique is the very much higher effective angular resolution. If the reason for the absence of narrow features in the emission observations is that the antenna beam is accepting many overlapping features which are not resolved, there should be a pronounced difference in the absorption and emission linewidths. The results are, at the moment, inconclusive. Clark, Radhakrishnan, and Wilson (1962) in a survey of 15 sources found a median dispersion of 2 km/sec, in agreement with emission results. Shuter and Verschuur (1964), however, found much narrower lines in their study of four bright sources. The narrow widths found are a direct result of the large number of separate Gaussian functions used to fit each spectrum, and the choice of the number of such functions is arbitrary. A better comparison with emission measurements may be possible with the use of large antennas to allow observation of weaker absorption lines at high latitudes.

On other grounds, however, the observed emission and absorption linewidths may not be strictly comparable, because we may not be observing on the average the same sort of cloud. In emission the brightness temperature:

$$T_B = T_m(1-e^{-\tau}),$$

where T_m is the harmonic mean of the T_{ex} of all the clouds along the line of sight, while in absorption,

$$T_B = -T_c(1-e^{-\tau}),$$

where T_c is the brightness temperature of the continuum source. (For a fuller discussion see Sec. II.) Suppose we are observing a source with T_c larger than T_m; then a cloud of fixed low optical depth which might not contribute significantly to an emission profile could contribute to the absorption in this source. Conversely, if T_c were less than T_m, such a cloud (of the same optical depth) seen in emission could be quite invisible in absorption. Furthermore, in a given cloud, since $\tau \propto N_H/T_{ex}$, an optically thin cloud would be expected to have a low density. In addition, since the cooling processes in interstellar clouds operate more slowly in low density clouds, the equilibrium T_{ex} in such a cloud would be expected to be relatively high. Thus a cloud of low optical depth would be hotter than the over-all average of all clouds. As we have seen, the average optical depth of clouds observed depends not only on properties of nature but on our observing methods—on the use of an emission or absorption technique and on the size of the antenna. Any interpretation of linewidths seen by different techniques is, therefore, influenced by a subtle, but important, selection effect.

The possibility of observing absorption and emission from a cloud extended enough to be visible in both is an interesting one, because one could then find the optical depth from the absorption and solve for the excitation temperature using the emission. The velocity dispersion in the lines would probably be larger than the pure thermal width expected from the measured T_{ex} ($T_{ex}=T_K$), and the remainder could be attributed to gas streaming in the cloud.

Another avenue for studying the velocity dispersion lies in the microwave spectrum of the OH radical (to be described in detail in Sec. VI). Absorption from interstellar OH clouds has been observed in the spectra of several sources. Barrett, Meeks, and Weinreb (1964) used high resolution observations of the OH lines in Cas A, which occur at the same velocity as HI clouds in this direction, to separate thermal and turbulent contributions to line broadening. Because the streaming motions do not depend on molecular weight, the contribution to the linewidths of this effect are the same for the two lines, while the thermal effects are different—the linewidths due to the latter effect are inversely proportional to the square root of the mass. Thus the OH lines are narrower than the HI lines. Barrett *et al.* found for two clouds kinetic temperatures of 90° and 120°K and turbulent velocities of 0.24 and 0.27 km/sec. If we assume that the turbulent velocities of these clouds are representative of clouds near the galactic pole, we can derive the kinetic temperature in this region as well. The result for the narrowest features ($\sigma=1.1$ km/sec) observed is 125°K, in agreement with the clouds in the direction of Cas A. However, if one considers from this point of view the dispersions in the four individual clouds mapped over angular extents of several degrees in this region (and described earlier in this section), one finds that the average thermal width is 2.2 km/sec and the kinetic temperature therefore 570°K.

We cannot at the present time conclude that we know the kinetic temperature in the interstellar gas, or even that there is a uniform value for this parameter over the whole galaxy. The solution to these problems is vital to our understanding of the heat balance in the gas.

C. Theories of the Velocity Field

We are now confronted with the problem of the dynamics of the interstellar gas. Any theory related to this problem must satisfy several observed conditions: (1) the gas occurs in the form of clouds; (2) these clouds are in motion partially in a systematic way; (3) the clouds have also a superposed random motion; and (4) the clouds have internal motions and a kinetic temperature which must in some way be related to the dynamics of the system as a whole. We shall deal first with theories for the maintenance of the random cloud motions and then with theories dealing with the establishment of the kinetic temperature of the gas.

It is clear that the random motions of interstellar clouds would soon die out if there were no kinetic energy added to the medium to sustain them. The clouds collide with each other rather frequently, about every 10^7 years, and the motions would soon be lost in these probably highly inelastic collisions. Attempts to find sources for the kinetic energy are hampered not only by the great uncertainties in the mechanisms of generation of such energy but by the unknown efficiency of conversion of this energy to motions of interstellar material. In addition, as we have pointed out, we do not know with any accuracy the average amount of random motion of the interstellar clouds. Several possibilities for accelerating mechanisms have been suggested (reviewed by Kahn and Dyson, 1965), and we take as a rough estimate of the energy dissipated in the cloud-cloud collisions a value of 5×10^{39} ergs/sec.

One possible source of the kinetic energy is the violent explosition of stars—the supernovae. The explosion injects into the interstellar medium a portion of the material of the star at high velocity. The amount of kinetic energy available from each such explosion is extremely difficult to estimate since only four have been observed in our galaxy (in 1006, 1054, 1574, and 1604), where estimates of the amount and velocity of the material are possible. Minkowski (1964) finds an average kinetic energy of about 10^{50} ergs from each supernova on the basis of the small amount of information available. An even greater source of uncertainty in discussing supernovae as a source of kinetic energy lies in the attempt to estimate the rate at which these events occur. The most recent estimate, which is a lower limit, is that one supernova explosion occurs every one thousand years (Minkowski, private communication). This leads to an input of kinetic energy into the interstellar medium of 3×10^{39} ergs/sec, about the amount required. The uncertainty in this estimate is obviously enormous, and the details of the communication of the motion of the ejected shells of gas to the interstellar medium are unknown. Obviously, this theory requires that the efficiency of conversion of the supernova energy into translation energy of the clouds must be high.

Another source of energy is the acceleration of clouds in the neighborhood of H II regions (Oort, 1954). One expects the gas in H II regions to acquire velocities of 10 km/sec, or energies of the order of 5×10^{11} ergs/g. If the H II region lies in a dense H I cloud, a shock wave can develop which accelerates a much larger amount of neutral gas, up to about 40 times the mass of the H II region. This would then come to 2×10^{12} ergs/g for each occurrence of an H II region. If each part of the interstellar gas becomes involved in such a situation once in 10^8 years, over the whole system a kinetic energy of 6×10^{39} ergs/sec is available. The numbers used in making this estimate, which again turns out to be adequate, are obviously very uncertain.

This mechanism of interaction between H II regions and the interstellar gas has been suggested as an important factor in a cycle of the growth and fragmentation of clouds (Oort, 1954; Field and Saslaw, 1965). It is suggested that a cloud starts in this cycle by the acceleration of a small region of high density near an expanding H II region. The cloud grows in size by processes of coalescence in cloud–cloud collisions until it reaches a mass great enough (~6000 solar masses) to make self-gravitation dominant and gravitational fragmentation a possibility (discussed by Spitzer, 1966). The result is a group of young stars which ionize the surrounding gas and thus begin the cycle again.

A more violent energy source related to H II regions is the rocket effect proposed by Oort and Spitzer (1955), which could accelerate a few clouds to quite high velocities by the sudden heating by a hot star of one side of a large dense cloud of hydrogen at some distance from the star. In this case, the outward acceleration of the cloud is determined by the reaction of the ionized gases which shoot out towards the star, exactly as in an ordinary rocket. The cloud must be very large, some thousands of times the mass of the sun, in order that a part of it can remain neutral and react to the motion of the ionized part. The simplified picture described by Oort and Spitzer has raised many questions concerning the details of such an intrinsically complex problem. Twenty-one centimeter observations of H I may be able to contribute to their solution because some of the clouds accelerated by the mechanism may be directly observable. One likely case is that of the California Nebula (NGC 1499), which is an ionized hydrogen cloud with a velocity of about 59 km/sec with respect to a nearby group of stars (the Zeta Persei association). The proposed sequence of events is that a neutral cloud was shot off from the association and in it there subsequently was formed a new star. The star ionized part of the cloud, making it visible optically. If some neutral hydrogen remains, it should be observable around the ionized region and should have the same velocity. We would then deduce the total amount of momentum imparted to this particular cloud in this particular "rocket."

We turn now to a problem intimately related to that of finding the driving force for the motions of interstellar clouds—finding the sources of heating and cooling of the gas. The path followed in this search has been a somewhat zig-zag one with the ultimate goal being the production of the observed kinetic temperature. Following the comprehensive study of the problem by Spitzer (1954), new mechanisms for each of the processes were sought, each to balance the heat generated or lost by the processes so far suggested. This is, of course, a perfectly legitimate procedure, but two kinds of problems interfere with it. One is the appalling number of assumptions necessary to calculate the heating and cooling rates for each mechanism. The other is the difficulty, described earlier, of establishing the goal of the search—the observed kinetic temperature of the gas.

We first describe the proposed heating mechanisms, then the cooling processes and finally the temperatures derived from the combination. Several articles reviewing the subject in detail are available (Takayanagi, 1964; Takayanagi and Nishimura, 1960; Kahn and Dyson, 1965) so that this will be only a brief résumé.

Among the possible heating agents the two that are most likely to be effective are cloud–cloud collisions and ionization by low-energy cosmic rays. In discussions of both these processes a large number of unknown quantities limit severely the calculation of the rates with which they proceed. The cloud–cloud collision theory (Kahn, 1955a) depends on the conversion of random cloud motions into heat at the time of collisions. In order to estimate the gain in thermal energy due to such collisions one must use a mean velocity of random motion of the clouds as a whole, which is hard to find even in a restricted region and impossible over the galaxy as a whole (see Sec. IIA). In addition, one must estimate the time interval between collisions, which also depends, of course, on cloud sizes and the number of clouds per unit volume. Finally, one must estimate the degree of inelasticity of the collisions. This last point illustrates the interrelation of the theories for motions of the interstellar gas, because if the collisions are completely inelastic and the heating mechanism efficient, the random motions will die out in about 10^7 years. In which case we are forced to say either that the clouds are young or are being continually fed energy from elsewhere, or that the collisions are nearly elastic and the postulated mechanism for heating the gas is ineffective. On the assumption of a random velocity of 7 km/sec, a density of ten hydrogen and 1.5 helium atoms per cm^3, time between collisions of 7×10^6 years, and completely inelastic collisions, the gain due to the process of cloud–cloud collisions is

$$\Gamma_{cc}\cong3\times10^{-26}\ \text{erg cm}^{-3}\ \text{sec}^{-1}.$$

This process depends linearly on the density of the clouds. The second heating process is the ionization of atoms in the interstellar clouds by low energy cosmic rays, called suprathermal particles by the proponents of the theory (Hayakawa, 1960; Takayanagi and Nishimura 1960; Hayakawa, Nishimura, and Takayanagi, 1961; Takayanagi, 1964). The proposal is that these low-energy cosmic rays (between 10 and 100 MeV) ionize the hydrogen atoms (the cross sections for ionization increase rapidly at these low energies), thus adding electrons with considerable velocities to the medium. The principal unknown in this mechanism is the flux of the low-energy particles. There is no direct evidence for the cosmic-ray energy spectrum in this low-energy range, because only high-energy galactic cosmic rays can penetrate the solar system's magnetic field. Thus, the low-energy cosmic-ray spectrum must be extrapolated from the 1-BeV range—a very dubious process. On the basis of an assumed flux of 40 particles/cm^2 sec (and for a cloud with a number density of 10 hydrogen atoms/cm^3) the gain in energy by this mechanism is

$$\Gamma_{CR} \cong 1.6 \times 10^{-26} \text{ erg cm}^{-3} \text{ sec}^{-1}.$$

[This rate is, like Γ_{cc}, also linearly dependent on $n(\text{H})$.] This is comparable to the heating by cloud–cloud collisions. It should be noted that both heating processes are more efficient in high density clouds than in low.

There are other possible heating mechanisms, each with its own set of assumptions, but they are thought to be less important than the two described. One is the ionization of various other atoms in the gas by ultraviolet radiation, rendered less efficient by the low abundance of the atoms. Other possibilities are the photodetachment of electrons from grains and the degeneration of turbulent energy into heat.

For the cooling of the interstellar gas once it has been heated by one or both of these agents there are three reactions which are probably important. The first one suggested was the excitation of low-lying levels of the positive ions, especially C^+, Si^+, and Fe^+, by electron impact, followed by the emission of radiation (Seaton, 1958). The rate of this cooling depends critically on the excitation cross sections and on the abundance of the ions. The latter factor is very uncertain not only because of the difficulty in estimating relative abundances throughout the galaxy but of the unknown amount of these elements which is tied up in grains and not contributing to the cooling. Since these elements contribute also to heating at the time of their ionization by ultraviolet radiation, the difference in loss and gain must be evaluated. The rate also depends on the temperature and the square of the absolute number density of hydrogen atoms. The loss in energy by this process at 100°K and for Seaton's estimate of relative abundance is

$$\Lambda_{ei} \cong 3.6 \times 10^{-25}\, n(\text{H}) n(e).$$

The second important cooling mechanism is probably the excitation of low-lying rotational levels of molecular hydrogen by collision with hydrogen atoms followed by emission of infrared radiation. The dependence of this mechanism on the kinetic temperature makes it a candidate for a primary role in cooling only above about 500°K (if the density is as low as is expected). Aside from the problems associated with the details of the excitation and radiation, this mechanism is uncertain because of its dependence on the abundance of H_2 in the interstellar gas. No observational evidence for the presence of H_2 has ever been found, much less a basis for estimating the density. The cooling rates have been calculated on the basis of a number density of $10^{-4} n(\text{H})$, a number by no means in agreement with the density suggested by possible formation mechanisms described in Sec. V. The value derived there is between three and five orders of magnitude greater. To complicate the problem further, the cooling rate is dependent on the square of the number density of hydrogen atoms. For a temperature of 500°K, the assumed H_2 abundance, and $n(\text{H}) = 10$, the cooling rate is 2.75×10^{-28} ergs/sec, of the same order as the electron–ion-impact cooling rate; at 100° the rate is only 2.80×10^{-30} ergs/sec. A possible observational check on the mechanism would be observations above the earth's atmosphere in the 10- to 100-μ wavelength region where the radiation from this cooling process appears.

A third possible cooling mechanism is the excitation of oxygen by collisions with hydrogen atoms rather than with electrons (Burgess, Field, and Michie, 1960; Field, 1962). The rate of energy loss again depends on the abundance of the ion and on the square of the number density of HI, and in addition on the probability of de-excitation per collision. If this probability is about 0.1, the cooling rate is comparable with that for electron–ion cooling at 100°K.

Two other presumably less important cooling mechanisms are the collisions of atoms with grains and the collisional excitation of molecules such as CH, CN, and OH. In both cases the low number density of the particles makes the process of no importance in ordinary HI clouds. Clouds with either an abnormally high dust content or an unusually great abundance of these molecules (and there is evidence for the existence of each) could well be cooled more effectively by these mechanisms.

The processes for heating and cooling the gas can be seen to be extremely uncertain both in concept and in detail. If we try, nevertheless, to see what sort of equilibrium temperature is established with several alternatives for the parameters, we can gain some insight into the problem. If first we assume the cloud-cloud collision process to be the principal source of heating, we can describe the cooling which occurs after a collision which heats the gas to several thousand degrees. Figure 2 (Takayanagi and Nishimura, 1960)

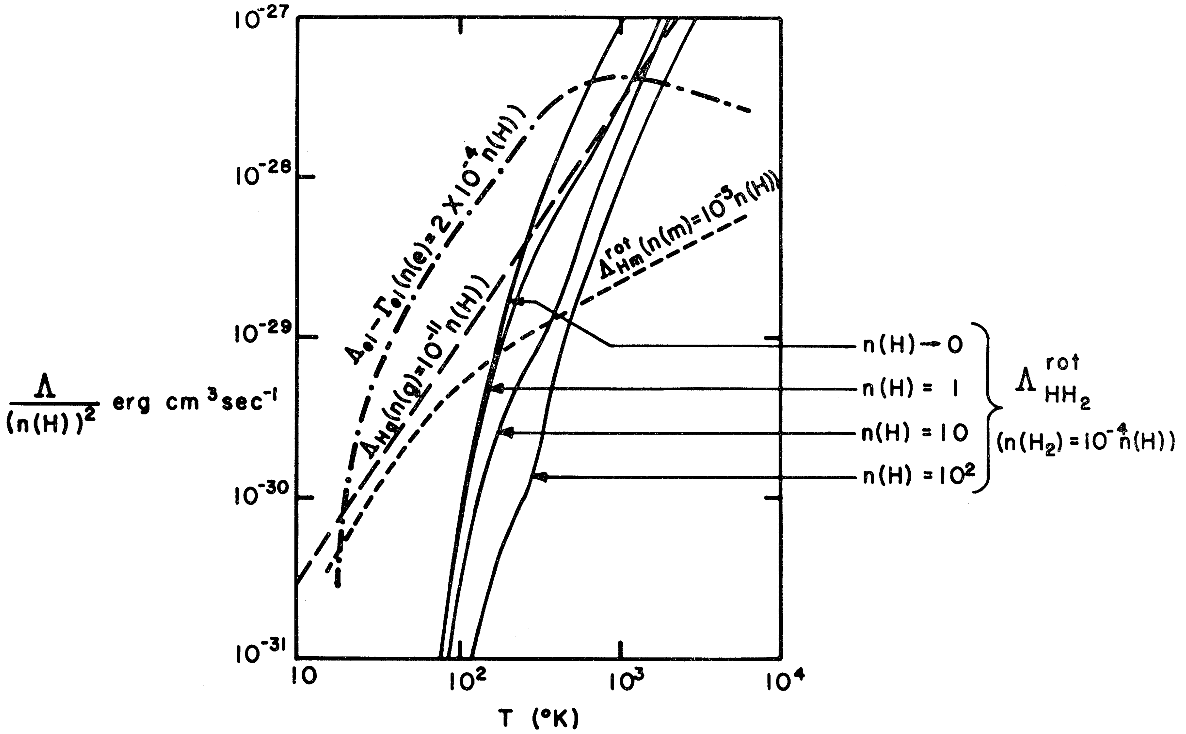

FIG. 2. Cooling rates as a function of temperature and composition of interstellar clouds (Takayanagi and Nishimura 1960). By excitation of low-lying levels of positive ions: $\Lambda_{ei}-\Gamma_{ei}$. By rotational excitation of H_2 by collisions with H: $\Lambda_{HH_2}^{rot}$. By rotational excitation of other molecules: Λ_{Hm}^{rot}. By collisions of H atoms with grains: Λ_{Hg}.

shows these cooling rates as a function of the temperature and of the density and the abundance of various constituents. For several combinations of these processes harmonic mean temperatures have been calculated. If, for instance, the cloud collision frequency is once in 5×10^6 years, and the initial temperature (after collision) is 3000°K, the harmonic mean temperature will be 60°K for a cloud with $n(H_2)=10^{-3}$ and $n(e)=2\times10^{-3}$. Each of these values may well be larger and the temperature consequently lower; in addition, the cooling by collisions of hydrogen and oxygen atoms (about equal in effect to electron collisions) has not been included. A similar analysis of the situation with cosmic-ray heating leads to about the same temperature—much lower than the usually quoted 125°K.

The uncertainty in the harmonic mean temperature from an observational point of view makes it impossible to say that any combination of the theories is totally inadequate. This is suggested by the fact that the equilibrium temperature depends on the density of the cloud. The two principal heating mechanisms proposed depend on $n(H)$ while all the cooling mechanisms depend on $[n(H)]^2$. A low density cloud will therefore on the average be hotter, and hence of lower optical depth.

It is perhaps appropriate to quote a paragraph from E. N. Parker (1958) in relation to problems of interstellar dynamics:

> "Most of the interesting theoretical problems in interstellar dynamics are entirely nonlinear, involving the simultaneous and coordinated functioning of several physical processes. Hence we cannot construct a rigorous, general, quantitative theoretical treatment of the interstellar problem. . . . Someday our understanding of compressible, radiating, supersonic, hydromagnetic motions in a tenuous gas may develop to the point where most of the contemporary uncertainties can be decided on a more rigorous basis."

III. INTERSTELLAR GRAINS

A. Introduction

The dark patches that exist in the Milky Way were the first indication that the interstellar medium contains obscuring matter. Although these regions could be due to a lack of stars, the fact is that dark patches are in reality globules of obscuring matter. The concentration of this matter to the plane of the Milky Way gives rise to the so-called "zone of avoidance." Furthermore, the spectra of reflection nebulae were found to be very similar to that of the central stars, suggesting that obscuring matter in the nebulae is scattering light from the stars.

Further investigations have shown that the apparently clear regions of space also contain the interstellar obscuring matter. In 1930 Trumpler (1930a, b) showed that the apparent diameters of galactic clusters increased with distance. Since this seemed unreasonable it implied that the distances estimated from apparent and absolute magnitudes of the stars in the clusters were wrong, probably overestimated due to interstellar extinction of the starlight.

The interpretation of the extinction agents as interstellar grains follows from a consideration of "Oort's limit" and the extinction properties of various atomic, molecular, and dust-like particles. "Oort's limit" (Oort, 1932, 1960) refers to the total density in the solar neighborhood. This quantity is derived by considering the observed acceleration law of the stars in a direction perpendicular to the galactic plane, which measures the total accelerating mass in the plane. From the velocity statistics of certain groups of stars, Oort derives a value for the total density of 10.2×10^{-24} g/cm^3. Thus, the extinction agents must have a density consistent with this limit.

The extinction observed is about 1 magnitude per kiloparsec. To explain the extinction by electron scattering requires about 500 electrons/cm^3, a totally unreasonable value in HI regions. The density of neutral atoms required to give the observed amount of extinction by Rayleigh scattering would also violate "Oort's limit." Thus, the atomic and molecular constituents of the interstellar medium cannot explain the observations.

The early observations (Trumpler, 1930c) showed that the extinction (defined as the sum of absorption and scattering) increases approximately monotonically with $1/\lambda$. We thus speak of interstellar reddening since the radiation from a star is "reddened" as it passes through the interstellar medium. This fact implies that the obscuring matter consists of some type of composite particles—the interstellar dust or grains, since individual atoms or molecules cannot give such a λ^{-1} law. Furthermore, this dust component can give the required extinction with a density several orders of magnitude below "Oort's limit."

Further verification that the obscuring agents are grains came from polarization observations. Hiltner (1949) and Hall (1949) attempted to detect polarization in hot, luminous stars following a suggestion by Chandrasekhar (1946) that the light from the edges of these stars would be polarized due to electron scattering. To isolate the limb of the star, eclipsing binary systems were used, in which a large cool star periodically occults the edge of the hot star. It was found, however, that occultation was not necessary to detect polarization. A constant amount of polarization was found throughout all phases of the binary system.

The polarization was found in other types of stars and the position angles of the electric vector were practically parallel for each of the stars in any region of the galaxy. The effect decreased with latitude and was found to be positively correlated with the distance of the star. Finally, it was noted that interstellar extinction was a necessary but not sufficient condition for polarization. Thus, we conclude that polarization is due to the grains which lie between the earth and the stars. To explain the polarization effect, preferential alignment of the particles was postulated. The mechanism generally accepted is magnetic alignment of slightly asymmetric grains.

Thus, we see the great importance of observations of interstellar extinction and polarization and of theories relating to the grains. The grains are an important constituent of the interstellar medium. They probably exert an influence on molecule formation in the regions between the stars, as we shall see in Sec. V, and are probably involved in the formation of new stars. The grains may exert an influence on energy exchange in HI regions; the temperature of the gas is effected by inelastic collisions with the grains. One method of inferring the magnetic field of the galaxy consists in using the observed polarization in conjunction with a suitable theory. In general, we use the grains as a tracer for conditions in the interstellar medium. Finally, the grains play the important negative role of extinction agents. The astonomer is thus faced with the operational problem of determining the amount of extinction in order to determine astronomical distances from the measured apparent brightness and the known absolute brightness of different objects.

The next sections summarize present knowledge regarding the interstellar grains. The observations of extinction will be treated first since the grain models are based primarily on these observations. After the three major theories are discussed, we shall show how the theories influence the interpretation of the polarization data. Next, we consider the interaction of HII regions and grains. Finally, the problem of the interstellar diffuse lines is discussed.

B. Observations of Extinction

The observations of extinction are important in two respects: (1) evaluation of the correction to observed magnitudes and colors to translate these quantities into intrinsic magnitudes and colors, and (2) providing a discrimination between differing theories of the grains. Figure 3 shows a schematic reddening curve as taken from Greenberg (1963). U, B, V, R are the ultraviolet, blue, visual, and red magnitudes on the Johnson and Morgan (1953) magnitude system. We see that in the visible portion of the spectrum $A\propto1/\lambda$ (A is the normalized extinction in magnitudes). At small λ^{-1} the curve behaves as if the wavelength is greater than the particle size, producing a situation analogous to Rayleigh scattering ($A\propto\lambda^{-4}$). At large λ^{-1} 's the curve looks as if the particle size is much greater than the wavelength and geometrical ($A\propto1/\lambda^{0}$) blocking is

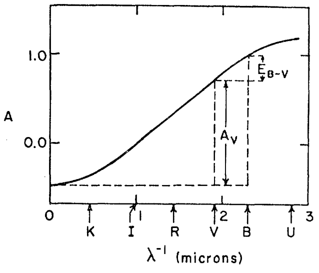

FIG. 3. Schematic extinction curve (Greenberg 1963). A is the normalized extinction in magnitudes. The inverse wavelengths corresponding to the U (ultraviolet), B (blue), V (visual), R (red), I, and K magnitudes are indicated. The color excess $E_{B-V}=A_B-A_V$.

occurring. Thus, the reddening curve indicates that the grains are approximately of the same size as the wavelength in the visible region—an important clue to the theories of the grains.

To correct the observations for extinction it is convenient to define R as

$$R=A_V/(A_B-A_V)=A_V/E_{B-V},$$

where E_{B-V} is called the color excess; this quantity is the easily determined difference between the measured B-V color and the B-V for an unreddened star. The color excess is a measure of the slope of the reddening curve in the visible region. It is important to consider R for three reasons: (1) As will be shown, A_V is hard to determine for one particular star. Thus, if R is known for the particular region, A_V can be obtained from the directly obtainable E_{B-V}. (2) Up to the present, astronomers have generally assumed that R is a constant of the interstellar medium. All corrections for extinction and hence distance determinations have been based on a constant value of R. (3) The fact that R will be shown to vary from region to region indicates that previous distance determinations may be in error. The variations in R also indicate that the distribution and possibly types of grains are not uniform throughout the interstellar medium. The value of R in a particular region gives some information on the grain distribution in that region.

Two methods of determining R and testing its constancy over the galactic plane are available. The first is the color-difference method. This method utilizes multicolor broadband photometry or spectrophotometry (evaluating the reddening in the star's continuum by a dispersing element) to compare the colors of unreddened and reddened stars of the same spectral type. The color difference method yields the extinction curve up to a small λ^{-1}. To obtain the zero point, an extrapolation must be made to $\lambda^{-1}=0$. Then one measures A_V/E_{B-V} from the curve. To be successful, observations in the far infrared must be used in order to achieve the best possible extrapolations. This method is the only method available outside of clusters to obtain R.

The second method, the variable extinction method, enables us to test for neutral absorption; i.e., extinction independent of λ. With this method R is determined directly from observations of distant clusters in which the color excesses vary across the cluster; we tacitly assume that R is the same throughout the cluster and that all the stars are at the same distance. The difference in apparent visual magnitude and absolute visual magnitude is plotted versus E_{B-V}. The slope of the linear relation is R. The major problem here is determining the star's absolute magnitude from its spectrum and the setting up of an accurate absolute magnitude calibration.

The most thorough investigations of the extinction curve have been published in the past few years. Johnson (1965) has used both methods to compute R in several regions. He uses the variable extinction method in six clusters to compute R. His results indicate the range of R from region to region is $3\leq R\leq 6.6$. He also obtains regional mean reddening curves by the color-difference method using broadband photometry from the ultraviolet to 10.45 μ. He then extrapolates to $\lambda^{-1}=0$ to obtain the zero point of the reddening curve. Five of the regions have zero points determined by the two methods. The zero points agree reasonably well. Johnson has proved that the extrapolation in the color-difference method is meaningful only if observations extend to the 10-μ region. The agreement of the two zero points implies that neutral absorption must be quite small. However, two stars (ι Aurigae and α Leonis) are quite anomalous and can be explained in terms of neutral absorption by particles 3–5 μ in diameter. Johnson has also proved that $R=3$ is a minimum value. Since astronomers in the past have generally assumed $R=3$, distances have been overestimated.

In addition, Johnson has shown that the detailed shapes of the reddening curve differ from region to region. Figure 4 shows his regional extinction curves. The NGC 2244 and Cepheus curves show sinuous variation at large wavelengths. According to Johnson, these can be explained by particles with a bimodal size distribution, with peaks near 0.3 μ and 3 μ. It is quite obvious that the reddening law is different in various regions of the Galaxy.

Johnson and Borgman (1963) determined R for stars at different longitudes by the variable color method from broadband photometric methods (ultraviolet to 3.5 μ). They found that R varies as a function of galactic longitude l and goes through a minimum at $l=110°$. The spread in R at certain longitudes is quite large. Furthermore, at a fixed l, as we move away from the plane the spread in R becomes quite pronounced for regions away from the galactic plane. As Johnson (1965) points out, the variation of R with l seriously distorts the true picture of the galactic spiral structure. The determination of accurate distances is quite a subtle problem.

Nandy (1964, 1965) has recently reported on very accurate spectrophotometric extinction measurements in Cygnus and Perseus in the wavelength range 8000 Å to 3400 A. He obtains the extinction curve at many more points than the broadband measures and thus is able to detect small changes in the slope of the curve. The extinction curves for Cygnus and Perseus differ significantly and each has a change in slope for $\lambda^{-1} > 2.3$—it appears that two straight lines intersect at $\lambda^{-1} = 2.3$; the change in slope in the Perseus curve is greater, however, than in the Cygnus curve. This observation is quite significant for the graphite grain theory.

A recent series of observations of extinction of six stars in the rocket ultraviolet at 2600 Å and 2200 Å has been reported by Boggess and Borgman (1964). (In Fig. 5 the two far ultraviolet points are shown). These observations may be quite significant in deciding between the various grain models since the different types of grains have different behaviors in the ultraviolet. Of the six stars only two of the stars' extinction curves could be determined accurately at the ultraviolet wavelengths. Furthermore, the interpretation of the observations is hindered by uncertainties in the intrinsic colors of the stars at these wavelengths. The consensus is, however, that the qualitative features of these observations are correct. The surprising result is that the extinction is found to be much greater than the theories would predict. We comment later on this discrepancy and the attempts to explain it.

The observations clearly show that the extinction curve differs greatly from region to region. It appears that grains have different properties and distribution laws throughout the galaxy. As Wickramasinghe and Guillaume (1965) point out, the existence of the so-called "uniform extinction law" prior to 1960 raised a very serious theoretical problem. This law implied that the mean particle size had to be specified to within a few percent in order to fit the observations. Thus, it was difficult to comprehend how this precise size could be established throughout the Galaxy. The new observations remove this difficulty.

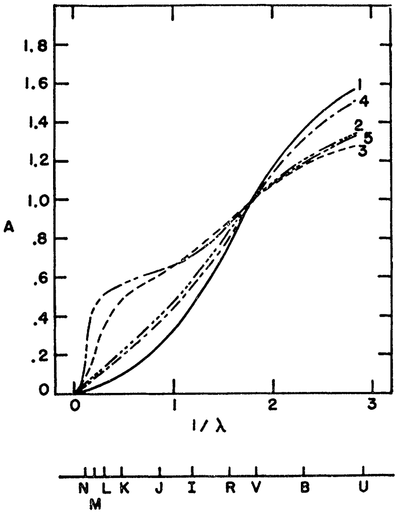

FIG. 4. The regional extinction curves of Johnson (1965). The data have been normalized to $A_V = 1.00$ mag. The regions are identified as follows: (1) Perseus, (2) Orion Belt, (3) NGC 2244, (4) Cygnus, and (5) Cepheus.

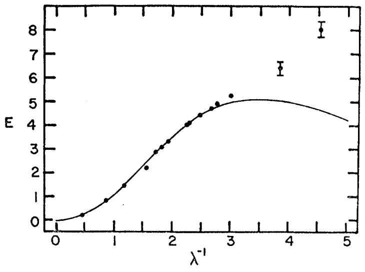

Fig. 5. Normalized extinction curve (Boggess and Borgman 1964). The two ultraviolet points of Boggess and Borgman at 2600 Å and 2200 Å are shown with error bars. The remaining observational points are taken from Johnson and Borgman (1963). The solid curve is van de Hulst's (1949) curve No. 15, based on the dielectric grain model.

C. Theories of the Grains

1. Dielectric Particles

To understand the complexity in the observations, several theories of the interstellar grains have been proposed. The first objective of the theories is to reproduce the observed extinction curve and secondly to predict optical properties, temperature, and composition of the grains. The observations yield limitations on the size, form, and numbers of any type of grains proposed in each of the theories. We consider first the dielectric grain model developed primarily by van de Hulst and Oort. Next, we consider the "Platt particle" theory and finally the graphite grain theory as developed by Wickramasinghe and Hoyle.

The dielectric grain or "dirty ice" model as developed by van de Hulst (1946, 1949) and Oort and van de Hulst (1946) considers that the grains grow from the interstellar gas by accretion. This hypothesis is based on the fact that where there is a large amount of gas, as revealed by interstellar lines, there is also a large amount of extinction—hence grains. On this theory the formation of the dielectric grains follows in three steps: (1) condensation nuclei of large molecules form out of the gas, (2) the abundant gases strike the nuclei and adhere (except H and He), and (3) the grains strike each other in cloud–cloud collisions and vaporize, thus leading to a steady-state distribution of grain sizes.

Step (1) is the weakest point of the theory. Following the work of ter Haar and Kramers (1946), it is supposed that diatomic molecules such as CH, and CH^+ are formed by radiative capture (more is said of this in

Sec. V on molecule formation) when two atoms collide. It is then possible that polyatomic molecules form. The details of this portion of the dielectric grain theory remain to be worked out.

The next phase is the growth to several thousand Ångstroms ($\sim 10^{-5}$ cm) by accretion. The final composition is independent of the nature of the condensation nuclei. The important parameters for accretion are the density of the grain material, the gas density, the accommodation coefficient (the fraction sticking), the kinetic temperature of the gas, and the temperature T_g of the grains. The T_g determines to a great extent what atoms will condense onto the grains. This temperature is determined by radiative processes; the kinetic energy exchange due to impinging atoms has a negligible effect on the grains. The equation of energy balance is

$$\int_0^\infty C_{ab}(\lambda, a)R(\lambda)\, d\lambda = \int_0^\infty C_{ab}(\lambda, a)B(\lambda_0, T_g)\, d\lambda.$$

The left-hand side gives the energy absorbed; C_{ab} is the absorption cross section; $R(\lambda)$ is the intensity of the interstellar radiation field. The right hand side gives the energy emitted; $B(\lambda_0, T_g)$ is the Planck function for T_g. The C's are computed using the Mie theory.

If the particle radiated as a blackbody, its temperature would be ~3°K. The particle at this temperature absorbs the visible and ultraviolet light of stars and emits infrared light with a wavelength exceeding its size. (We have seen that the particle size is of the order of several thousand Ångstroms.) These particles have a low emissivity compared to a blackbody in the infrared and the particle thus attains the higher temperature of 10°–20°K. The actual value is unknown, and it is found that T_g apparently increases with decreasing size of the grain (Greenberg, 1963).

The temperature of 10°–20°K means that H and He does not condense permanently since these atoms quickly evaporate at this T_g. Heavier atoms do, however, remain. In particular, van de Hulst considers that most of the oxygen atoms impinging on the grain remain permanently. They eventually become part of a water molecule after being bombarded by hydrogen atoms. The water molecule is quite stable and becomes the major constituent of the grain. Other molecules which contain the less abundant metallic elements exist in smaller proportions. Based on the above T_g and cosmic abundances, van de Hulst gives the following model for the grains: Each particle has 100 molecules of H_2O, 30 molecules of H_2, 20 molecules of CH_4, 10 molecules of NH_3, 5 molecules of MgH, etc. The resultant particle has a complex index of refraction: $m \approx 1.3-0.05i$. The nature of the electrical charge of the particle is still unclear; this charge, as we will see, is important in considering the motion of the grains with respect to a magnetic field and in considering the interaction of positive ions with the grains in the process of molecule formation. The general consensus is that the grains have a slight negative charge due to the higher velocities of electrons than positive ions. An equilibrium is reached when the electrostatic repulsion of the electrons and the attraction of the ions offsets the difference in the number of collisions due to the higher velocities of the electrons (van de Hulst, 1948).

We turn now to a discussion of the third process in the Oort–van de Hulst theory: the establishment of an equilibrium size distribution of grains. Van de Hulst and Oort computed that a particle would reach a size of 10^3 Å in about 3×10^7 years. Since this is appreciably less than the time scale of the Galaxy (10^{10} years), some process must be considered which prevents the particles from growing beyond the several thousand Ångstrom range. Furthermore, the process of reaching an equilibrium distribution must be fairly uniform since variations in the extinction law indicate that effective particle sizes differ at most by a factor of two. It is quite obvious that the exhaustion of the gas cannot be the limiting factor in the grains' growth since gas is observed in the same place as grains. Four processes to limit growth will be considered: (1) evaporation of the grains, (2) photodissociation of the atoms and molecules in the grains, (3) destruction during grain–grain collisions, and (4) sputtering by atoms in cloud–cloud collisions.

Process (1) has already been mentioned; most of the H and He evaporates since the vapor pressure of these two gases exceeds the partial pressure in the gas. In order to test the idea that the grains are completely evaporated, Wickramasinghe (1965) has made detailed calculations of the process of an encounter of a gas-grain cloud with a Strömgren sphere of a young, hot star. He adopts $T_g = 100$°K as the temperature required to vaporize the grains in a time scale less than the time for the cloud to transverse the Strömgren sphere. He finds that for cloud radii of 2–3 pc only extremely bright O stars can destroy a sizable fraction of the grains. Since these stars are relatively rare, Wickramasinghe concludes that evaporation is a rare event in destroying the grains.

Process (2) consists in either the photodissociation of a molecule near the surface and escape of one of the atoms or a release of an atom from a crystal by means of a light-quantum. Cosmic rays may also be of importance in this connection. The consensus is that these processes would not destroy the grain, only modify its surface. However, details are lacking due to our ignorance of the crystal structure of the particles and of the low-energy cosmic-ray (suprathermal particles) density.

The third process, grain–grain collisions, was initially proposed by Oort and van de Hulst (1946) to limit the growth of the particles. The basic mechanism here is that in cloud–cloud collisions two grains will collide and the energy will be sufficient to vaporize the particle. These collisions take place with a mean time of one per

10^7 years. Using the properties of the dielectric grains, Oort and van de Hulst conclude that a head-on collision with $v > 2.8$ km/sec will lead to vaporization. Using the estimated properties for the clouds and grains, they derive the probability p per unit time that an ice grain of radius r is removed by the collision process:

$$p = 8.7(r/10^{-5})^3 10^{-9} \mathrm{yr}^{-1}.$$

For $r = 10^{-5}$ cm we have an average lifetime of $\sim 10^8$ years. Since this is about 10^{-2} times the life of the galaxy, we may conclude that an equilibrium situation exists between growth and destruction. Oort and van de Hulst then derive the distribution function $n(r)$ of sizes of the particles. The final result may be represented by

$$n(r) = n(0) \exp\{-0.69(r/r_{\frac{1}{2}})^{2.6}\},$$

where $r_{\frac{1}{2}}$ is the radius at which $n(r)/n(0) = \frac{1}{2}$. The form of the distribution does not depend on the shapes or distribution of the interstellar clouds. This picture has many uncertainties about it. The data on the frequencies, sizes, and motions of interstellar clouds are quite uncertain. There are no clear-cut observational tests for cloud–cloud collisions, although Oort (1946) and van de Hulst (1948) have suggested that the energy freed by the collision can provide an explanation for the luminous rims of dark nebulae.

Recently, the cloud–cloud destruction mechanism has been criticized. Cloud collisions may not be completely inelastic due to the presence of large magnetic fields which prevent free penetration of the colliding clouds (Takayanagi and Nishimura, 1960). Also from a microscopic point of view, the charge of the grains may cause the grains to move in circular orbits about the magnetic field with gyroscopic radii of $10^{12}-10^{13}$ cm and this may prevent interpenetration of the grains from two clouds (G. B. Field, private communication).

In view of the above objections, the sputtering process must be considered. Wickramasinghe (1965) has considered this process in detail. He considers that in cloud–cloud collisions the kinetic temperature builds up to ~ 3000°K as the translational velocity of the clouds is converted into internal energy of the clouds. The grains are bombarded by atoms with an average energy of 0.3 eV. Since the vaporization energy of a water molecule from ice is ~ 0.2 eV, it is possible that some of the ice could be ejected. Wickramasinghe points out that sputtering is a momentum transfer process and not a mechanism of local heating of the irradiated surface. Using a semi-empirical relation, he concludes that H atoms with energy of 2 eV or more have a probability of at least $\frac{1}{4}$ of releasing a lattice molecule from the grain. He derives the rate of diminution of the grain:

$$dr/dt = -2 \times 10^{-9} \exp\{-2/kT\} \mathrm{cm\ yr}^{-1} \quad (k \text{ in eV deg}^{-1}).$$

The probability per unit time that an ice grain will be destroyed by sputtering is $p \cong 10^{-8}$ yr^{-1}; this holds for all radii not greater than several thousand Angstroms. In contrast to the Oort–van de Hulst theory, this probability is independent of size. The Oort–van de Hulst process is less efficient than the sputtering process for removing ice mantles with radii $\leq 10^3$ Å.

Next, given this probability, Wickramasinghe derives the size distribution of the grains that results from the sputtering process:

$$n(r) = n(0)e^{-r/\bar{a}},$$

where $\bar{a}$ is the mean size. Thus, the two processes give different types of distribution laws.

Given these two types of particle distributions, we next discuss the attempts to reproduce the observed extinction curve. We will investigate the possibility of choosing between the two, thus arriving at conclusions regarding the grain destruction process. All theoretical and observational results are normalized to some convenient scale. The calculated extinction is then proportional to:

$$Q(\lambda) = \int_0^\infty Q_{\mathrm{ext}}(r, \lambda)\pi r^2 n(r)\, dr.$$

$Q_{\mathrm{ext}}(r, \lambda)$ is the efficiency factor for extinction (cross section/area) for a particle of radius r at wavelength λ. Van de Hulst (1949) attempted to fit the observations of extinction using the Oort–van de Hulst distribution function. He chose $m = 1.25 - 0.03i$ for the complex index of refraction. Using the Mie theory for Q_{ext}, he found the best fit with the extinction curve with his curve number 15, reproduced as a solid line in Fig. 5. For this particular fit, $r_{\frac{1}{2}}$ (the radius at which $n(r)/n(0) = 0.5$) is ~ 3000 Å. Unfortunately, there is no unique solution for $r_{\frac{1}{2}}$ and for m. We must make an estimate for m from the composition of the particle.

As Fig. 5 indicates, the Oort–van de Hulst theory does not give agreement with the ultraviolet points of Boggess and Borgman; the change in the character of the theoretical curve indicates the importance of ultraviolet observations. Krishna Swamy (1965) has attempted to fit the ultraviolet observations by including the wavelength dependence of the real part of the index of refraction (van de Hulst assumed this was constant). Krishna Swamy found that with a smaller $r_{\frac{1}{2}}$ (~ 2000 Å) the theoretical curve constructed with the Oort–van de Hulst particle distribution agrees well up to the 2600-Å observation; however, the theoretical curve begins to flatten and falls well below the 2200-Å point. Wickramasinghe, Ray, and Wyld (1966) attempt to explain the observed extinction curve, including the two ultraviolet points at 2600 Å and 2200 Å, by the sputtering distribution function. They find that they can get a very good fit to the observations up to $\lambda \simeq 3000$ Å if $\bar{a} = 750$ Å and a reasonably good fit at 2600 Å. Again, the 2200-Å point falls well above the theoretical curve. Thus, we cannot make a direct test of the Oort–van de Hulst particle distribution versus the sputtering particle distribution due to the fact that a reasonably good fit to the observations (excluding the two ultraviolet points) can be attained with both distributions. We are forced to agree with van de Hulst (1964): "Fitting a theoretical curve to these data . . . is (unfortunately) rather easy."

One further observation may be of significance in accepting or rejecting the dielectric grain model. In the second flight of Stratoscope II (infrared observations from high altitudes by means of a balloon), a reddened late-type supergiant was investigated in the far infrared. Danielson, Wolf, and Gaustad (1965) have attempted to locate an absorption band in the spectrum of the star due to ice in the region of 3.1 μ. They use van de Hulst's curve number 15 and the observed A_v as the basis for the expected strength of the band, assuming that the grains are entirely ice. No band is found. These authors conclude that no more than 25% of the interstellar grains can be ice. Although the exact interpretation of these results is not clear, they may well be an argument in favor of other types of particles.

2. *"Platt Particles"*

One of the various problems in the dielectric grain theory is the formation of the grains. Van de Hulst assumed that all possible reactions involving abundant atoms which satisfy energy considerations would occur. Since the chemical composition of the grains determines the optical properties, it is necessary that we understand, in addition, the condensation and adsorption processes which take place on the surface of the grains. Donn (1955) has criticized the van de Hulst formation process. He cites several experimental studies which indicate that the surface reactions would be very inefficient at the temperatures of interstellar space. In particular, he considers the formation of H_2O molecules by surface reactions of H_2 and O; there is some experimental evidence that this reaction is quite inhibited at low temperatures. The formation of H_2O is, of course, central to the Oort–van de Hulst theory. However, very little is known about surface reactions at low temperatures and extrapolation from higher temperatures to 10°–20°K is far from satisfactory.

Following these criticisms, Platt (1956) made a proposal for a new type of interstellar dust particle; this type of particle has subsequently been known as a "Platt particle." Platt's basic premise is that the particles grown by accretion from a gas containing ions or molecules and subjected to constant radiation damage will not have filled electronic bands. They will not be any more chemically stable or electrically neutral than the ions and radicals of which they are formed. Even if a system were to reach a situation where all of its energy bands were full, there are more ways of losing this property than preserving it. Platt proposes that a large free radical of size 1–10 Å is formed by accretion. He then uses theoretical and experimental arguments to assert that the longest wavelength of absorption in a particle of radius r caused by a one-electron jump between free electron levels is about 800 r. Finally, on the basis of crude experimental data, Platt proposes that the absorption cross section of the particles is approximately constant with wavelength and equal to the geometrical cross section down into the ultraviolet.

Due to the lack of a suitable theory, the detailed wavelength dependence of extinction caused by this sort of grain remains unknown up to the present. No really significant observational test using the extinction curve is possible, since the optics of these particles are unknown. The only definite conclusions we obtain from this rudimentary theory are that the particles will be small $(1-10$ Å$)$, that the total mass of absorbing material will be about 1/200 that of the dielectric grains, and that the extinction curve will not have a strong dependence on the exact size of the particles.

An interesting attempt to treat the "Platt particles" in detail has been made by Kimura (1962). His proposal is based on the hypothesis due to Hayakawa (1960) that the cosmic-ray flux (the suprathermal particles) in the region 0.1 to 100 MeV is substantial. (See Sec. IIC for further discussion of the suprathemal particles.)

Kimura states that dielectric grains would initially form as in the Oort–van de Hulst theory. After detailed calculations concerning the interaction of the cosmic-ray protons and alpha particles with the grains, he derives the probability per unit time that a particle of radius r is destroyed:

$$p=3\times10^{-6}\ \mathrm{yr}^{-1}.$$

Thus, in comparison with the p given by the cloud–cloud collision in the Oort–van de Hulst theory, the cosmic-ray destruction process will be quite effective in limiting the growth of grains with radii less than 100 Å.

Using the above p, Kimura derives the size distribution function for the particles as $n(r)=n(0)\exp\{-r/\bar{a}\}$ the same function that Wickramasinghe derives for the sputtering process. Kimura then attempts to calculate a theoretical extinction curve for these particles. Since no detailed information on the wavelength dependence of the extinction to be expected is available, he uses two simplified types of absorption coefficients as suggested by Platt.

$$\begin{array}{lll}\text{Case A:} & Q_{\text{ext}}=\pi r^2 & \lambda\leq\lambda_m \\ & Q_{\text{ext}}=0 & \lambda>\lambda_m \\ \text{Case B:} & Q_{\text{ext}}=\pi r^2(\lambda/\lambda_m) & \lambda\leq\lambda_m \\ & Q_{\text{ext}}=0 & \lambda>\lambda_m,\end{array}$$

where λ_m is the longest wavelength of strong allowed absorptions $(\lambda_m=800r)$. With $\bar{a}=2$ Å, he is able to fit the observed extinction curve with Case B from the far infrared to 4000 Å. The ultraviolet points ($\lambda \leq 3500$ Å) which are a crucial test for any theory, show a great disparity between observations and theory. Since the Q_{ext} is only a crude approximation, even the partial agreement between theory and observation must be considered to be fortuitous. We again see how easy it is to fit the observed extinction curve with widely different theories. The imperfections in our knowledge of the optics of these particles thus prevent a detailed study of the "Platt particle" theory.

3. *Graphite Grains*

In 1954, Cayrel and Schatzman (1954) proposed that a component of the interstellar dust consists of graphite grains. Since 1962 Hoyle, Wickramasinghe, and others have investigated in detail the possibility of explaining interstellar extinction by graphite particles. We will consider the work of the latter authors in three parts: (1) the formation of the graphite particles, (2) the formation of the ice mantles over the graphite cores as proposed by Wickramasinghe, and (3) the attempts to explain extinction by these particles.

As we have pointed out, the major problem with the dielectric grain theory is the formation process; the low densities in the interstellar medium imply that the formation of condensation nuclei is a very slow process. Hoyle and Wickramasinghe (1962) attempted to overcome this problem by proposing that the graphite grains form in a high density environment—the atmospheres of C (carbon) stars. These are cool, luminous stars which have an abundance of carbon much greater than that of oxygen, in contrast to the sun where carbon is about half as abundant as oxygen. In the C stars' atmospheres the densities of monatomic and polyatomic carbon are appreciable. Among the C stars is one group, the N stars, which have large radii; these would contribute most of the interstellar graphite. Most of the C stars are variable; they pulsate with periods of ∼100 days. At minimum phase the surface temperature is ∼2000°K, and at maximum phase ∼2700°K. In contrast, the atmosphere of the sun is ∼6000°K.

Hoyle and Wickramasinghe consider in detail the manner in which graphite is formed in the atmospheres of the *N* stars and the method by which the graphite leaves the star and moves into the interstellar medium. They consider the concentrations of monatomic and polyatomic carbon; most of the carbon is in the form C_1, C_2, and C_3. The fact that a larger number of species (C_4, C_5, etc.) is not present in large concentrations means that fairly sizable grains will form, rather than a much larger number of small nuclei.

As the star cools below 2700°K when it goes from maximum to minimum phase, graphite begins to form as the partial pressure of carbon exceeds the vapor pressure of graphite. Once the graphite is formed, radiation pressure begins to act on the particles, which are shown to be less than 10^{-5} cm. This force exceeds the gravitational force and the particles begin moving away from the star. The escape of the grains is, however, hindered by the viscous drag produced as the grains encounter the gases in the star's atmosphere. The grains formed near minimum phase must escape before maximum phase since they all will be evaporated as the star heats up again. Approximately 10^7 sec is the time allowed for escape. Hoyle and Wickramasinghe show that the escape can take place if the gas density in the star's atmosphere remains below a certain upper limit for $\sim 10^7$ sec. This in turn implies that the temperature must remain below 2300°K for $\sim 10^7$ sec.

Once the grains leave the star no further condensation of carbon takes place. The grains are exposed to the star's radiation field and evaporation will take place unless the grains move several stellar radii in a relatively short time. Hoyle and Wickramasinghe show that the grains move at a high velocity and are at two stellar radii in $\sim 3 \times 10^5$ sec. Thus, the grains escape quite easily once they leave the stellar atmosphere.

A substantial fraction of the carbon in the atmosphere is said to escape during each cycle. Then the carbon is resupplied to the atmosphere by convection from the star's interior.

Finally, Hoyle and Wickramasinghe consider the amount of graphite interjected into the interstellar medium per year. Using the fact that there are 10^4–10^5 N stars in the galaxy and estimating the mass loss of graphite by these stars per cycle, they conclude that the present grain density of $\sim 10^{-27}$–10^{-26}g/cm^3 can be attained in $\sim 10^{10}$ years—the lifetime of the Milky Way.

As in the other grain theories, the formation of the graphite particles is the weakest point in the theory; although the general features seem reasonable, a more detailed analysis is needed. Furthermore, there are at present no observations that directly relate to graphite formation in the N stars' atmospheres. Tsuji (1964), in an investigation of molecular abundances in cool stars, has criticized the Hoyle and Wickramasinghe theory on two points: (1) the carbon is depleted as polyatomic molecules of carbon, hydrogen, and nitrogen form; thus, the amount of free carbon available for forming graphite is severely limited. (2) Tsuji states that Hoyle and Wickramasinghe adopt a value of the saturated vapor pressure of graphite which is too small. Hence, the graphite will begin to form at ∼2200°K and not at 2700°K; this effect also results in a reduction of the amount of graphite which will form.

The final step in the growth process is the formation of ice mantles in the interstellar medium. Since graphite is strongly chemisorbent, practically all the heavy atoms will be adsorbed. Hydrogen can then combine with the oxygen and a mantle of predominantly ice will grow.

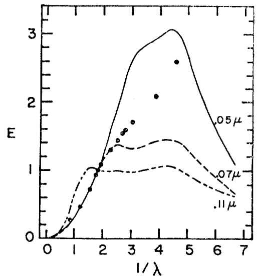

FIG. 6. Normalized extinction E versus $1/\lambda$ (λ in microns) for graphite spheres of various radii (Wickramasinghe and Guillaume 1965). $E=1$ at 5470 Å. The closed circles represent the observational extinction curve of Boggess and Borgman (1964, see Fig. 5).

Since the graphite grain of size ~100 Å will acquire a mantle with radius ~1000 Å in 10^8 years, Wickramasinghe (1965) considers processes which are effective in mantle removal; if these processes are not efficient, the composite grains will acquire the optical properties of the dirty ice grains. Wickramasinghe considers the three major processes mentioned in the section on dielectric grains: (1) evaporation in grain–grain impacts during cloud–cloud collisions, (2) sputtering by H atoms in cloud–cloud collisions, and (3) thermal evaporation by encounters with O and B stars. The graphite is not affected by any of these processes since the heat of vaporization is 170 kcal/mole, as contrasted with 250 cal/mole for ice. For process (1) to be effective, the relative cloud velocities would have to be >20 km/sec—a totally unreasonable value. Since the composite grains are generally $<10^3$ Å, process (2) dominates as we have seen in the section on dielectric grains. An exponential distribution of mantle sizes results:

$$n(r)=n(r_0)\ \exp\ \{-(r-r_0)/(\bar{a}-r_0)\},$$

where r_0 is the graphite core radius and $\bar{a}$ is the mean mantle radius. Since the destruction process is so efficient, the mantle growth will increase the total radius by only two to three times. This will ensure that the optical properties of the composite particle are still determined primarily by the graphite cores.

Several attempts have been made to compare the extinction observations with the graphite theory. As in the other types of grain theories, the observations in the visible region are quite easy to fit with theoretically constructed curves. In order to explain differences in extinction, Wickramasinghe has proposed that in some regions graphite grains of size 200–1000 Å predominate, while in other areas the composite particles dominate. In either case, accurate extinction cross sections for various size particles as a function of wavelength are needed. Wickramasinghe *et al.* (Wickramasinghe 1966, Krishna Swamy and Wickramasinghe 1966, Guillaume and Wickramasinghe 1966) have used new experimental data on the wavelength dependence of the index of refraction of graphite from 1100 Å to the far infrared to calculate these cross sections for pure graphite grains.

Two significant results were found: (1) the absorptive index $k(m=n-ik)$ reaches a sharp maximum near 2600 Å. This feature may explain the large extinction measured by Boggess and Borgman (Fig. 5), which we have described in Sec. IIIB. However, as shown in Fig. 6, attempts to explain the observations in detail have not been successful. This figure shows three theoretical curves for $r_0=500$ Å, 700 Å, and 1100 Å; the observations of Boggess and Borgman are indicated by circles. It is evident, nevertheless, that the graphite grains are much more promising as an explanation for the 2600 Å and 2200 Å observations than the dielectric grains. (2) For $r_0<700$ Å, the extinction is approximately linear as a function of λ^{-1} in the region from 12 000 Å to 4300 Å. Below the latter limit, the extinction curves vary considerably depending on particle size. The linear part arises from Rayleigh scattering in the range of constant m and the variable portion arises from the fact that m ceases to be constant below ~4300 Å. This set of circumstances may well explain the break at 4300 Å in the observed extinction curve that Nandy has detected for Cygnus and Perseus. The theory predicts a nonlinear extinction for $\lambda<4300$ Å in contradiction to observation; however, Nandy and Wickramasinghe (1965) suggest that a collection of different mean particle sizes could give an approximately linear curve for $\lambda<4300$ Å.

Wickramasinghe, Dharmawardhana, and Wyld (1966) extend the above results by calculating extinction cross sections for graphite-core ice mantle grains. Three major effects are found. (1) The extinction at infrared wavelengths comes almost entirely from absorption arising in the graphite cores. For a core of radius 200 Å and with a mantle twice this size, 75% of the extinction at 6000 Å is due to absorption by the graphite core; in the blue and ultraviolet, scattering from the ice mantle contributes about 50% of the extinction. (2) the ratio $R=A_V/E_{B-V}$ is increased relative to a pure graphite grain. (3) Using various values of $\bar{a}-r_0$ in the mantle distribution law:

$$n(r)=n(r_0)\ \exp\ \{-(r-r_0)/(\bar{a}-r_0)\},$$

Wickramasinghe *et al.* show that practically identical extinction curves result provided the cores' radii are less than 600 Å. This effect is caused by the fact that the extinction due to the graphite cores is approximately linear in the region 12 500 A to 5000 Å and is independent of core radius. Hence, knowledge of exact values of core sizes is not necessary to predict extinction. To further test the theory Wickramasinghe and Nandy (1965) have attempted to fit Nandy's detailed observations of Perseus and Cygnus. For the former, they adopt a model of pure graphite grains, with a Gaussian distribution of radii with a dispersion of 100 Å centered at $\bar{a}=600$ Å. For the Cygnus observations, they choose a composite grain model with a sputtering distribution function of mantle sizes: $r_0=200$ Å, $\bar{a}-r_0=300$ Å. Since there are so many free parameters, these two models can scarcely be unique. Furthermore, it is very difficult to explain the existence of composite particles in one extended region of the Galaxy, while pure graphite grains exist in another. *A priori* the graphite grains would be expected to grow mantles unless very special conditions existed. In many respects, nevertheless, the graphite grain theory is very promising for explaining interstellar extinction. In the section on optical polarization (Sec. IIID1) we will express a further difficulty that the graphite grain theory encounters.

D. Further Observations

1. Optical Polarization

We next consider the question of interstellar polarization. Polarization does not provide the fundamental data on which the above theories of the grains are based. In a few cases however, as we will point out, the characteristics of the polarization have implications for the theories of the grains. In general, we must first have a theory for the grains in order to infer properties of the interstellar medium from the polarization data.

Two conditions are necessary to explain polarization: (1) asymmetric particles and (2) an alignment mechanism. The former is slightly different for each grain model while the latter is the same for all models. We shall first discuss the alignment mechanism and then investigate its operation on each of the three types of grains proposed. We turn then to a further discussion of the uniformity of the grains.

The theory of alignment in a weak magnetic field is due to Davis and Greenstein (1951). The grains are set spinning by the interstellar gas; angular velocities of 10^5–10^6 rad/sec build up. Since the smallest kinetic energy of rotation for a given angular momentum corresponds to rotation about the shortest axis of the ellipsoid of inertia, the grain tends to rotate about its smallest axis (Hall and Serkowski, 1963). The effect of paramagnetic relaxation then comes into play. For those volume elements which experience a changing magnetic field due to the orientation of the field with respect to the axis of rotation, paramagnetic absorption takes place. The energy in this mode of rotation goes partially into the internal energy of the grain. Therefore, these motions are damped out, and the particle tends to rotate with its axis of rotation parallel to the field; in the limit of complete alignment, the field in each part of the grain remains constant if the transverse gradient of the field is larger than the long dimension of the grain.

Davis and Greenstein are not able to solve the problem of the alignment exactly since the torques acting on the grain due to paramagnetic absorption are not conservative. An approximate solution for the size of the magnetic field is given by comparing the relaxation time for orientation with that for disorientation due to collisions with gas atoms. Two limiting cases are discussed: (1) the alignment is practically complete, and (2) the alignment is small. In case (1) they obtain

$$B > [a n_H T^{\frac{1}{2}} \omega / (7.5 \times 10^{18} \chi'')]^{\frac{1}{2}}, \tag{1}$$

where χ'' is the imaginary part of the magnetic susceptibility, ω is the angular velocity of the grain, a is the average radius of a grain, n_H is the number of gas atoms per cm^3, T is the kinetic temperature of the gas. The lower limit exists because of the obvious saturation effect in the alignment. This, then, is a measure of the magnetic field necessary to align the particles completely.

For slight alignment:

$$B = [a n_H T^{\frac{1}{2}} \omega F / (2.5 \times 10^{18} \chi'')]^{\frac{1}{2}}, \tag{2}$$

where F is the distribution parameter which is a measure of how well the particles are aligned. In order to estimate the magnetic field in this case we must find the degree of alignment by some other means. The quantity F can be determined by observing the ratio of polarization to extinction. This is related to F by

$$p/A_v = 4.5 \frac{(\sigma_E/\sigma_H - 1)}{(2\sigma_E/\sigma_H + 1)} F \sin^2 \theta, \tag{3}$$

where p is the amount of polarization in magnitudes, θ is the angle between the field and the direction of the line of sight, σ_E and σ_H are the cross sections that correspond to the axes of symmetry of the grain parallel to the electric and magnetic vectors of the incident light, respectively. Thus, the measured quantity p/A_v depends both on the degree of alignment F and on the degree of asymmetry of the particles. In order to find F from this equation we must have some independent idea of the degree of the asymmetry from the grain models.

To obtain B, F is calculated from (3) if θ and σ_E/σ_H can be estimated. If $F \cong \frac{1}{3}$ (complete alignment), Eq. (1) is used to obtain a lower limit to B. If $F \ll \frac{1}{3}$, Eq. (2) is used to obtain B.

The observations of polarization indicate that the plane of vibration is generally in the galactic plane. The Davis–Greenstein theory predicts that the long axis of the grain lies perpendicular to the field. Hence, we conclude that the field lies in the plane. If, in addition, one assumes that the field is along the spiral arms, the theory is also successful in explaining the longitude dependence of polarization. When we look along a spiral arm we look parallel to the field and the amount of polarization, p, should be zero. If we look across the spiral arm, the field is perpendicular to the line of sight and the polarization is maximized. The polarization goes to zero at $l = 50°$ and 230°. The direction of the galactic field as derived from polarization agrees quite well with the spiral arms as delineated by young clusters and associations. (In Sec. IV we will

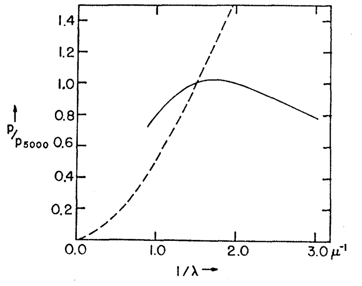

FIG. 7. Wavelength dependence of polarization. The solid curve is a theoretical fit (Greenberg, Lind, Wang, and Libels 1963) to Gehrel's (1960) observations. The dashed line represents Greenberg's (1966) calculations for small graphite spheroids. This curve is normalized to unity at $\lambda^{-1}=1.5$.

point out objections to this interpretation.) The theory also explains the correlation in filamentary nebulae that exists between the directions of the filaments and the position angles of the transmitted starlight.

We shall first describe the application of the Davis–Greenstein theory to dielectric (dirty ice) particles, where it was initially used. The problems of formation, comparison with extinction observations, and the determination of B will be considered. The anisotropy of the particles must be explained since the Oort–van de Hulst particles supposedly grow by random accretions. Two methods of explaining the anisotropy have been proposed. The first is that grain–grain collisions not energetic enough to vaporize the grains give rise to melting and the grains fuse to form elongated grains. Secondly, Kahn (1952) has suggested that the growth of ice particles is strongly influenced by the electrostatic potential due to the electric dipole moment of the H_2O molecule. He envisions the formation of H_2O on the surface of the grains, which then line up with existing molecules, thus giving rise to elongated particles. This theory does, of course, raise many unresolved questions.

The paramagnetic nature is attributed to small quantities of iron and iron compounds which the grain obtains in the random accretion process. We now examine these particles to see if they can produce both the observations of *extinction* and the color dependence of polarization. We cannot compare the situation analytically because no exact expressions are available for extinction cross sections for spheroids as a function of orientation. Approximate expressions have been developed by Greenberg (1960b), and he and his associates (Greenberg, Pedersen, and Pedersen 1961) have conducted microwave analogue experiments at 3 cm to measure cross sections of spheroids. The general conclusion is that the wavelength dependence of polarization of spinning particles is similar to that produced by perfectly aligned particles. Greenberg, Ling, Wong, and Libels (1963) considered the polarization due to long cylinders with an index of refraction of 1.3 and an Oort–van de Hulst distribution of radii. The wavelength dependence for perfect alignment is quite similar to the dependence found in the observations of eight stars by Gehrels (1960). The polarization reaches a maximum at about 6500 Å; it falls off rapidly to the infrared and gradually to the shorter wavelengths (see Fig. 7).

Next, we consider the determination of B for the dielectric grain model. Reasonable values of σ_E/σ_H are not much larger than one; if $\theta=90°$, the maximum value of (p/A) is observed and F is found to be about $\frac{1}{3}$, i.e., practically complete alignment. Using the theory of paramagnetic relaxation (1), Davis and Greenstein obtain $\chi''/\omega\simeq2.5\times10^{-12}/T_g$. Since $a\cong2000$ Å, $n_H=10/\text{cm}^3$, $T=100°$, and $T_g=10°$, they find $B>3\times10^{-5}$ G.

Two obvious problems arise from the above considerations. (1) The mechanism giving rise to the asymmetry of the dielectric grains remains to be fully explained. (2) The lower limit obtained for the general galactic field B is quite different from the value obtained from other considerations ($\approx10^{-6}$ G or less). (See Sec. IV.)

Henry (1958) proposed a solution for the second objection by considering the particles to be ferromagnetic. The particles attain a large residue of iron and iron compounds after selective evaporation in collisions. In this case, $\chi''/\omega\simeq3\times10^{-7}$ and $B>1.2\times10^{-6}$ G. However, the details of selective evaporation have not been considered.

The "Platt particles," or large free radicals, represent an attempt to overcome the first objection. Since the particles are so small, they are said to have aspherical shapes because of statistical fluctuations in the arrangements of molecules or atoms. The degree of asymmetry required can be estimated and compared with the expected size of such variations. If the particles are elongated with length/width $=1+\epsilon$, the maximum ratio of polarization to extinction is $\epsilon/2$ (Hall and Serkowski, 1963). Since the observed value for $(p/A)_{\max}$ is 0.06, $\epsilon=0.12$. As Greenberg (1960a) points out, this value is two or three times larger than the value obtained from random growth. Thus, we see that the problem of asymmetry is not entirely solved by invoking "Platt particles." However, these particles are highly paramagnetic and it is possible that the Davis–Greenstein effect could apply. However, no estimate for χ''/ω is available and hence no information on the magnetic field can be obtained.

We turn now to graphite grains which are able to overcome both objections to the dielectric grain model in a very effective way. First, the asymmetry required can be attributed to the intrinsic structure of graphite. The graphite has a conductivity perpendicular to the basal planes two orders of magnitude less than in the planes. Thus for light with the electric vector in one of the planes the grain produces metallic absorption, while for light with the electric vector perpendicular to the plane, the graphite has dielectric properties. The extinction cross section for the latter component is the smaller of the two. Second, the magnetic field required to produce the observed polarization is much smaller. Wickramasinghe (1962) gives a detailed discussion of polarization due to graphite particles. Since $\sigma_E/\sigma_H \gg 1$, we obtain $p/A = 2.25\ F \sin^2 \theta$. When $\theta = 90°$ the maximum p/A is obtained and we find $F = 0.02$, a very slight alignment. Then from a discussion of the magnetic properties of graphite, we obtain $\chi''/\omega = 1.2 \times 10^{-10}/T_g$; leading to an estimate of the field from Equation (2) of $B = 1.1 \times 10^{-6}$ G, more in line with the results from other considerations. In this model, the polarization is due primarily to the anisotropic conductivity of graphite rather than to a strong magnetic field.

One of the reasons the graphite theory was initially proposed was the ease with which the observed amount of polarization can be explained by these particles. Ironically, Greenberg (1966) has pointed out that the wavelength dependence of polarization may well rule out graphite particles as constituents of the interstellar medium. He considers the wavelength dependence of the polarization which would be expected from small oblate spheroids with major axes of 500 Å (a size which, as we have seen, will roughly reproduce the observed extinction curve). Greenberg finds that polarization rises monotonically from the far infrared to the ultraviolet [see the dashed curve in Fig. 7. The solid line represents the observations of Gehrels (1960).] If the graphite becomes covered with an ice mantle of moderate dimensions, the polarization would hardly be altered in the infrared; in the visible and ultraviolet, Greenberg proposes that the polarization would continue to increase as a function of λ^{-1} with a smaller slope. This result is in clear contradiction to the observations. Although the graphite grain model has several very attractive features, as we have mentioned in Sec. IIIC3, the above result is obviously a serious objection to this theory.

Up to now, we have not considered the relationship between extinction and polarization and the information available from the various models from this relationship. Several authors (Wilson 1959, Greenberg and Meltzer 1960, and Greenberg 1963) have attempted to show that changes in the wavelength dependence of extinction were due to orientation effects: when viewed along the lines of force all grains present themselves sideways; when viewed perpendicular to the lines of force they present themselves both sideways and edge-on. Greenberg (1960) then suggested an observational test to distinguish between dielectric particles and "Platt particles." He shows that the extinction curve due to the latter particles should be independent of orientation.

However, it now seems evident that any change in the extinction curve due to orientation is masked by differences in the particle size distribution and intrinsic properties from place to place. Wampler (1962) has looked for a correlation between fluctuations in the polarization (hence alignment) and deviations from a mean reddening law. He found that this effect does not exist; this conclusion is supported by Serkowski's results (1963). In fact, near $l = 130°$, where polarization is quite large, Wampler found the lowest value of the reddening slope.

A most important recent development in our understanding of the nonuniformity of the grains has been presented by Gehrels and Silvester (1965). They have made polarization measurements which give further evidence that the properties of the grains change from cloud to cloud; in some places not only the amount but also the position angle of polarization changes with wavelength. The nearby stars show no change as a function of wavelength, while the distant stars show a decided change with wavelength. The interpretation is as follows: The light from the star traverses several clouds. Each cloud has different size grains and hence a different distribution parameter $r_{\frac{1}{2}}$; thus the polarization due to each cloud will predominate at a particular wavelength, i.e., the clouds with small particles dominate the polarization in the ultraviolet. Finally, the magnetic field orientation changes slightly from cloud to cloud. Thus, the position angle changes as a function of wavelength. Again, we come to the conclusion that the grains are far from uniform throughout the interstellar medium.

We can also use the polarization data to answer a question which has long plagued studies of the interstellar medium: is the ratio of grains to gas (n_g/n_H) constant throughout the galaxy? Lilley's (1955) 21-cm investigation of the Taurus–Orion Dark Nebulae Complex indicates that on a large scale n_g/n_H is constant with position. In general, the ratio of the mass densities of dust to gas is found to be about 10^{-2}. On the other hand, Bok, Lawrence, and Menon (1955) show that on a small scale (in certain dark nebulae) n_g increases without an increase in n_H. As Hall and Serkowski (1963) have shown, a new method of attacking this question is provided by polarization measurements in open clusters. Since polarization and extinction have the same dependence on distance and galactic latitude (both depend on the grains), the stars at a given longitude normally show a strong correlation of polarization and extinction. However, the strange thing is that if the stars are grouped together at the same galactic coordinates and the same distance, as in a cluster, the observations indicate that the correlation between polarization and extinction is quite small. This lack of correlation can be explained if n_g/n_H is constant between the sun and the cluster. We have seen that polarization is directly proportional to n_g and to F. But F is inversely proportional to n_H for a fixed B [see Eq. (2)]. Hence, p is proportional to the ratio of n_g and n_H. If p is constant, the ratio n_g/n_H is constant. Thus, if the grain density in front of a particular star is larger than the average density, A_v

will increase for this star. The polarization will, however, remain constant since n_H increases in the same proportion as n_g. Thus, the polarization is not correlated with extinction for stars in open clusters, and this test indicates a constant n_g/n_H.

2. HII *Regions and Interstellar Grains*

Recently, the important problem of the relationship between HII regions and grains has been considered. As we will point out, these considerations may have important implications for molecule formation in HII regions.

The grains in the direction of the Orion Nebula were noted, in 1937, to have peculiar properties when Baade and Minkowski (1937) determined that the ratio of extinction to color excess was quite large in this direction. Recent measurements indicate that R is $\sim$7.5. Krishna Swamy (1965) has applied the Oort–van de Hulst distribution for "dirty ice" and attained a good fit to the observations with $r_{\frac{1}{2}}\simeq 4000$ Å, i.e., a relative depletion of the small grain sizes has occurred.

O'Dell and Hubbard (1965) have recently shown that part of the interstellar extinction in the direction of Orion occurs in the HII region. They have investigated the ratio of the brightness in the continuum to that in the second Balmer line (H_β) as a function of distance from the center of Orion at five wavelengths. They calculate the amount of scattering due to atomic processes and conclude that the major portion of the brightness in the continuum is due to scattering from dust particles in the HII region. $N_{\text{dust}}\,Q/N_{\text{gas}}$ is found to increase by a factor of ten from the inner to outer regions (Q is the effective scattering cross section for the particles). Hence, the cross section and/or number of particles is quite a bit smaller near the young, hot stars in Orion. O'Dell and Hubbard suggest two possible mechanisms to explain the apparent increase in dust in the outer regions and the anomalous reddening law: (1) radiation pressure drives the smaller particles out at a faster rate than the larger ones, and (2) the smaller grains are evaporated by the intense radiation field. The details of these mechanisms are not now known; the over-all effect depends on the lifetime of the nebula, which is given as 2×10^4 years by Vandervoort (1964) on the basis of the expansion of the gas due to ionization.

Finally, Herbig (1958) has shown that for the nebula IC 405 dust and gas coexist in space in a unique set of circumstances. The exciting star for this nebula is AE Aurigae, an O 9.5 (high luminosity and temperature) star moving away from the association of stars I Orionis. The star differs in radial velocity from that of the nebula by 37 km/sec. The nebula consists of two parts: (1) an emission nebula whose presence is indicated by hydrogen emission lines and (2) a reflection nebula of different shape and size, whose presence is indicated by a purely continuous spectrum. The first component shows up in photographs taken in the light of Hα (the first Balmer line). The second component shows in the blue regions of the spectrum which are free from emission lines. Herbig shows that the second component is probably due to scattered light from interstellar grains, since the nebula which has the continuous spectrum is coincident with dark lanes in the emission nebula. It seems that the dust does not share the motion of the star since obscuring lanes of dust are visible for some distance from the star. As we have seen (in Sec. IB), the presence of a reflection nebula or an emission nebula usually depends on the type of exciting star. The hot luminous stars give rise to emission nebulae and the cooler less luminous stars produce reflection nebulae. In the case of IC 405, both types are present. Herbig proposes that this situation is due to the large velocity of AE Aurigae: the dust has not had enough time to accommodate itself to the properties of the star. Presumably, if the star did not have the large space motion, only an emission nebula would be produced. In support of this contention is the fact that none of the dust lies directly to the south of AE Aurigae; this is the direction from which the star has come and there has probably been enough time for the grains in this region to have been evaporated by the star's radiation. The HII region is due to the encounter of the star with a low density gas cloud. Thus, we find the anomalous result that the material associated with the reflection nebula has little free gas associated with it. As Herbig points out, this conclusion is contrary to the idea that the grains "... are only trace condensates from gas, and hence should have a large amount of gas still associated with them since no efficient separation processes are known."

3. *The Unidentified Diffuse Lines*

As a conclusion to the section on interstellar grains we briefly consider another observational component of the interstellar medium which seems to be related to the grains—the group of "diffuse unidentified lines." About twenty of these discrete spectral features in a very high frequency should [have been] used since absorption have been presently discovered in the range 4000–6800 Å (Herbig, private communication). These features have half-widths of up to 10 Å as contrasted with several hundredths of an Ångstrom for the atomic and molecular lines, as indicated in Table I. The diffuse absorption lines remove about six times as much light from the spectra of background stars as do the atomic and molecular lines. These lines always appear at the same wavelengths but the shape of the line profiles and the ratios of strengths vary from star to star.

Observations of diffuse lines have established three boundary conditions (Herbig 1963):

(1) The strength of the lines is more strongly correlated with the amount of interstellar extinction than

with the number of Ca^+ atoms in the line of sight. Wampler (1963) has also shown that the strength of the strongest diffuse line at 4430 Å is strongly correlated with the slope of the reddening curve determined in the same region of space. It seems that extinction and the strength of 4430 vary as a function of galactic longitude in the same manner. These facts indicate that the carrier of the diffuse lines is in some way closely associated with the interstellar grains.

(2) The carrier seems to be disrupted by the presence of an HII region since the diffuse lines are weakest in these regions. This fact may be connected with the anomalies in extinction near HII regions.

(3) The strength of the diffuse features implies that the carrier consists of abundant elements.

As Herbig (1963) points out, one of the most surprising things about the diffuse lines is that they have yet to be explained. The lines were actually discovered in 1921; their interstellar origin was shown 15 years later. There have been numerous attempts at explanation—the main problem being the explanation of the large widths of the lines. The first attempts involved diatomic and polyatomic molecules. Recent attempts by Unsöld (1964) (plasma oscillations in solids) and by Herbig (1963) (metastable H_2 molecules on interstellar grains) have not been successful in providing a full explanation. Quite probably, the solution to the problem of the diffuse lines will come after we attain a more complete understanding of the nature of the interstellar grains.

IV. GALACTIC MAGNETIC FIELDS

The interstellar grains were the first observed tracer of a galactic magnetic field and are believed to be a catalyst in the formation of molecules. The next two sections deal with these aspects of the interstellar medium.

For many years astronomers have accepted the idea that the galaxy is influenced by magnetic forces in addition to the gravitational ones. The presence of ionized gases in motion which would produce a magnetic field, and of cosmic rays distributed isotropically as seen from the earth, which would result from the existence of such a field, have contributed to this acceptance. However, the strength and topography of this field remain uncertain. Since the influence of the field is likely to be important, a lack of knowledge of its size and direction spawns a variety of theories based solely on guesses of these quantities. The intriguing thing about the problem of the magnetic field at this moment is that the crucial question of the importance of its influence on motions of the interstellar gas requires for its answer observations lying at the limit of sensitivity of current instruments. If the field is of the order of 10^{-5} G, it dominates the motion of the gas, and if it is of the order of 10^{-6} G, it exerts very little influence on the motion. These limits arise because the balance of the kinetic energy of the gas clouds and the magnetic energy associated with the field changes radically between these two values of the field strength; that is, if $B \geq 10^{-5}$ G, the magnetic pressure is larger than the pressure due to cloud–cloud collisions. It is also just in the range of 10^{-5} to 10^{-6} G that the observational techniques reach their sensitivity limit.

There are several different avenues for investigating the galactic magnetic field; investigation of the alignment of interstellar grains, the intensity and polarization of the galactic background radiation at radio frequencies, the rotation of the plane of polarization of distant discrete radio sources, and the Zeeman splitting in spectral lines. None of these is entirely satisfactory. In all cases but one there is a significant piece of the puzzle missing in the attempt to deduce the nature of the field from the observations. In that one case, the Zeeman splitting of the interstellar neutral hydrogen line at 1420 Mc/sec, observations refer to conditions in individual clouds, which may not give a valid picture of a general galactic field, if any. Although all the techniques are ambiguous and extremely difficult from an observational point of view, serious attempts to study the magnetic field continue because of its importance to the structure of the galaxy and to the physical condition of the interstellar material.

The first observation to be interpreted as direct evidence of the presence of a galactic magnetic field was that of the polarization of starlight. As we have stated in Sec. IIID1, this observation, although of fundamental importance, is not sufficient in itself to establish the size of the magnetic field. The missing piece of the puzzle in this case is the vital one—knowledge of the nature of the grains producing the polarization. The range in possible fields, depending on the model of the grains adopted, is 10^{-5} to 10^{-7} G—just too large to contribute definitively to a resolution of the current dilemma.

There are then very great difficulties in relating the observed interstellar polarization of starlight to a quantitative discussion of the strength of the magnetic field. The polarization does tell us, however, the average orientation of the field along the line of sight to the star. It must be perpendicular to the line of sight in the directions in which we observe the effect. In addition, the predominant appearance of the electric vectors parallel to the galactic plane indicates that the field is preferentially also parallel to the plane. The field so defined can not, however, be said to be a general galactic magnetic field. The polarization must be quite a local phenomenon since it must occur between the star and us, and distant stars which might show distant conditions are obscured by the very dust which would outline the field for us. In addition, a very interesting correlation with the polarization of nonthermal radio radiation further suggests that the effect has a very

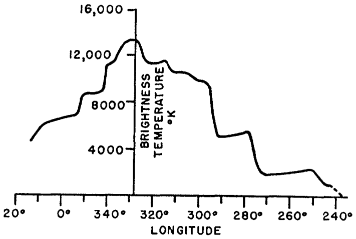

Fig 8. Longitude distribution of 85.5-Mc/sec radiation in the galactic plane (Mills 1964). Location of the steps is approximately coincident with directions tangential to spiral arms.

local origin, and this point will be discussed in a later part of this section.

We have further evidence on the strength and topography of the magnetic field from quite another kind of observation. This is the measurement of the intensity of the galactic background radiation at long radio wavelengths. This was, in fact, the first observation made in radio astronomy, and remains an area of active interest both because of its implications for the structure of the galaxy and because the problems associated with it are by no means solved. The early history of the problem is described by Grote Reber (1958), the man whose capacity for wonder led him to begin the serious exploration of radio astronomy. He describes the two fundamental problems as "How does the cosmic static, at any given frequency, change in intensity with position in the sky; and how does cosmic static, at any given position in the sky, change in intensity with frequency?" In broad terms we know the answers to these questions, but by no means in the detail which would give us real physical insight into the conditions in the interstellar medium which influence their answers. We know, for example, that the intensity of radiation increases in the direction of the galactic plane, and in particular in the direction of the center, but we do not yet understand its relation to spiral structure nor the degree to which its origin lies in individual sources. Concerning the frequency dependence, we have improved on the situation facing Reber, who writes, "Thus, on the face of the prevailing ignorance, a very high frequency should [have been] used since much better resolution would be secured and very much more energy would be available for measurement." The second of these reasons was based on the assumption that the radiation had a dependence on frequency given by the Planck function, increasing in intensity in the radio region as the frequency squared, the so-called thermal emission. Reber himself discovered before long that the frequency dependence is quite the opposite, and the radiation, therefore, is nonthermal. It is now believed to be the result of the synchrotron radiation of relativistic electrons spiraling in the galactic magnetic field. A measurement of vital importance is the frequency dependence of this radiation. It is, however, very difficult to obtain because of the presence of thermal radiation in unknown amounts in just the directions in the galaxy where the nonthermal radiation also appears. (See Mills, 1964, for a comprehensive review of the subject.)

The importance of the frequency dependence lies in the interpretation of the synchrotron mechanism in terms of the conditions in the galaxy. If we assume that the relativistic electrons have an energy spectrum of the form

$$N(E)dE = KE^{-\beta}\,dE,$$

the synchrotron energy radiated per electron is

$$I_\nu = f(e, m, \beta) H_\perp^{(1+\beta)/2} \nu^{(1-\beta)/2},$$

where $H_\perp$ is the field perpendicular to the line of sight. If we wish to use this equation to estimate the galactic magnetic field, we must know the parameters in the electron energy spectrum, and we can only get at them indirectly. The exponent, β, in the energy distribution appears also in the exponent of the frequency in the equation for the radiated energy, and is therefore observable. The accepted value of β, with recognition of its uncertainty, is 2.2. In order to use this radiation as a measure of the galactic magnetic field, we must know, in addition, the electron energy flux, represented by the parameter K. Measurements of the electron flux in the high atmosphere of the earth give a value for this flux, which is not at all certain to be representative of the flux in the galaxy in general, principally because of the probable influence of the sun on the flux in our neighborhood. If the value measured by Earl (1961), of 1.5×10^{-3} electrons $\text{cm}^{-2}\ \text{sec}^{-1}\ \text{sr}^{-1}$ with energies greater than 10^9 eV, is taken to be representative, the measures of the intensity of the radiation by Mills lead to a value for the magnetic field in the plane of about 3×10^{-5} G.

One must, however, be careful to notice the fact that this deduced field is actually only the component of the field perpendicular to the direction of motion of the electrons and depends also on the direction of the line of sight to the observer. If α is the angle between the magnetic field vector and the direction of observation, the intensity of the observed radiation detected is

$$I_\nu \propto (\sin\alpha)^{(1+\beta)/2}.$$

The degree of angular dependence of the radiation, thus, also depends on the characteristics of the electron energy spectrum. In any case one would expect that in directions parallel to the magnetic field vector one should see no radiation at all. A test of one of the theories of the structure of the galactic field is therefore possible. This particular theory states that the field is aligned along the spiral arms. The observation by Mills (1959), shown in Fig. 8, of an increase in long wavelength radiation in directions along which one is looking tangentially at a spiral arm, and where one is therefore looking parallel to the field, devastating as it may seem, has not entirely ruled out the theory. It has been suggested that one needs only to allow the field lines to be "tangled" somewhat with root mean square irregularities of about 20° (Brown and Hazard, 1960; Field, 1960). In order to interpret observations of the intensity of the nonthermal radiation in terms of the size of a galactic field, one must know in detail the nature of this tangling, because only the lines intersecting the line of sight close to the perpendicular direction will contribute to the measured intensity. That the lines cannot be strictly parallel to the arms is clear from the observations, but whether the irregularities are random or systematic, in or out of the plane, is not known. One possible model is that in which the lines of force spiral about the arms to give this effect. Hoyle and Ireland (1961) and Ireland (1961) have developed this theory, and Ireland has described the effect of a tightly wound spiral in terms of interstellar polarization of starlight. Since the polarization of starlight is a highly local phenomenon, the predictions of the theory might better be compared with the intensity of the nonthermal radio emission.

Observation of the intensity of the galactic background as a function of position and frequency cannot alone give us a description of the galactic magnetic field. Our interpretation of the measurements depends on our estimates of the electron energy spectrum at a place quite inaccessible to us and on our models for the topography of the field itself.

The synchrotron emission has inherent in it another clue concerning the fields in the region in which it originates. That is, the radiation is known to be polarized in a direction perpendicular to the lines of force of the magnetic field. This would be an ideal property to use to separate the effects of orientation and strength of the field, but for the fact that we look through a long path length to observe the polarization. It is very likely that the integrated radiation along the line of sight is effectively depolarized for two reasons. One is the tangling of the field in the region of production of the radiation and the other is the irregularity of this field along the line of sight to the region of production. As a consequence, we observe polarization of the background nonthermal radiation only from regions very close to us in the galaxy; that is, from the same sort of volume as is observed in observations of the interstellar polarization of starlight. The causes of the polarization are quite different but the effectively limited field of view is the same.

Indications from the measurements of polarization of long wavelength radio emission over the whole sky are that, indeed, the phenomenon is a local one. Mathewson and Milne (1965) find that the areas of intense amounts of polarization are not correlated with intense amounts of radiation. In fact, the regions of high polarization are quite localized and lie in a band about 60° wide along a great circle coming high out of the plane. One of the places of intersection of this circle with the plane is at $l^{\rm II}=160°$—just where the most intense interstellar polarization of starlight occurs. In addition, the intrinsic direction of the plane of polarization of this radiation lies parallel to this great circle (Mathewson, Broten, and Cole 1966). (It should be emphasized that the optical polarization is an effect which can accumulate along the line of sight, while the radio effect can only be destroyed by Faraday rotation.) The magnetic field is indicated by the radio observations to be parallel to the plane, but the polarization effects are not confined to the plane—even reaching the galactic pole. Mathewson and Milne (1965) interpret the large scale distribution of polarization as indicating that the sun lies almost at the center of a spiral arm which has a magnetic field directed along it towards $l^{\rm II}=70°$ and 250°. They also derive a value for the strength of the field of 5×10^{-5} G, but this is based on a number of assumptions, especially with regard to the distance and cross section of the radiating regions.

We have still another indication that there is a galactic magnetic field, one which is again, however, dependent on unknown factors. This is the observation that the emission from some distant radio sources which are intrinsically polarized show the effects of traversing a medium with free electrons and magnetic fields. The position angle of the electric vector of this radiation varies with the square of the wavelength in just the way characteristic of Faraday rotation (Gardner and Whiteoak 1963). This rotation is described in terms of a rotation measure, the slope of the line showing this wavelength dependence. This rotation measure can be written

$$\text{R.M.}=\int_0^s n_e B_{||}ds,$$

where n_e is the electronic density, $B_{||}$ the strength of the magnetic field parallel to the line of sight, and s the distance over which the radiation encounters the rotating medium. A fundamental unknown is the amount of Faraday rotation which occurs in the source itself. Any dependence of the rotation measure on galactic coordinates indicates that some of the effect occurs in our galaxy. There is apparently a correlation of rotation measure with latitude, at least in the sense that the scatter of values is larger near the plane than far from it. We would expect this from the greater complexity along the path length in the plane, both in terms of magnetic field strength and direction and in terms of variations in electron density. The total amount of Faraday rotation is a cumulative effect of the medium along the line of sight and hence is an indication of average conditions along that line. There appears also to be a weak correlation with galactic longitude, in the sense that some regions tend to have positive rotation measures and others negative, the sign being determined by the direction of the field. The suggestion of Morris and Berge (1964) is that the local field is aligned along the nearby spiral arms since they find maxima in the rotation measures near the longitudes at which this arm is tangential to the line of sight.

An interesting comparison of the rotation measures with the polarization of the long-wavelength background was made by Mathewson and Milne (1965).

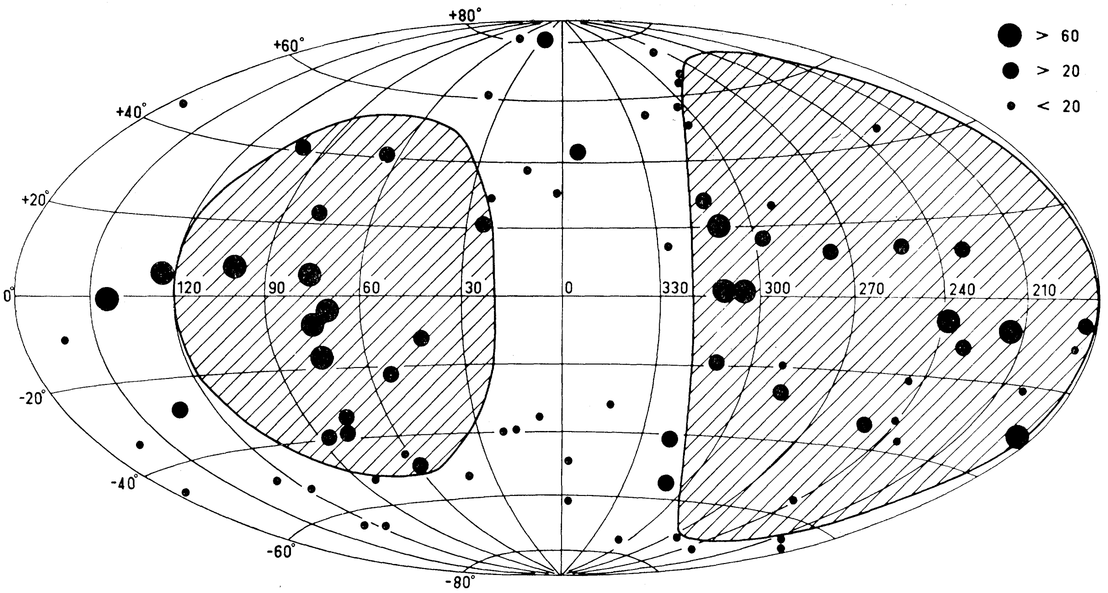

Fig. 9. Comparison of polarization and rotation measure as a function of galactic coordinates (Mathewson and Milne 1965). Area of maximum polarization of 408-Mc/sec radiation is unshaded. The points are the rotation measures of the discrete sources.

They showed that the regions of high polarization are regions of low rotation measure—especially if one looks at the latitude and longitude dependence together. This is consistent with the fact that (1) the degree of Faraday rotation of the plane of polarization of a source depends on the component of a magnetic field which lies along the line of sight, and (2) the amount of polarization of radio emission produced by the synchrotron mechanism depends on the component of the field which is perpendicular to the line of sight. Figure 9 shows the rotation measures of Gardner and Davies (1965) (separated into three groups, >60, >20, <20) and the areas of polarization. The unshaded area is the 60° band which contains most of the long-wavelength polarization. This suggests that the amount of rotation of the plane of polarization of distant sources is also very dependent on local conditions.

In investigating Faraday rotation we are dealing with a phenomenon which depends on the parallel field component, not the perpendicular, as in the intensity of the nonthermal radio emission. Here we are confronted with having to imagine the field lines tangled in such a way as to lead to the presence of enough lines perpendicular to the field for production of the radiation, and enough remaining undisturbed to produce rotation which depends on those parallel to the line of sight. Without knowing the degree and nature of this tangling we are at a loss to use these observations to determine the strength of the magnetic field from them. In addition there is another unknown factor, the electron density. In the equation for the rotation measure we have two factors which can vary by large amounts. The electron density in a region where hydrogen is not ionized at all is of the order of $10^{-4}/\text{cm}^3$ or less, while in regions where hydrogen is partially ionized it may be as high as $1/\text{cm}^3$ and still not be obvious on photographs as an emission region. The path length, s, can be anything from a few tens of parsecs, if the rotation occurs in an isolated cloud, to thousands of parsecs if the rotation occurs all along the path length and the source lies close to the direction of the galactic plane. This leaves $B_{||}$ practically indeterminate.

Faraday rotation in the galaxy probably contributes to another observed effect. The percentage of linear polarization in some sources is much smaller than would be expected for radiation produced by the synchrotron mechanism, and the percentage varies with the wavelength of observation. It is possible that this "depolarization" (so-called because the percentage of polarization usually decreases with increasing wavelength) is due to differential Faraday rotation of different parts of the source due to the medium between us and the source. If there are regions small in angular size compared to the source and with differing density or fields, each will rotate the plane of polarization at any wavelength by different amounts and, hence, reduce the integrated amount of polarization. If one now observes at a longer wavelength, the amount of rotation for each small region will be greater and the difference between them also greater, so that the integrated effect will be to reduce the degree of polarization. If this depolarization could be related to irregularities in magnetic field in the galaxy, we would have some indication of the scale of such irregularities. One problem is that we do not know the percentage of polarization of the radiation as it emerges from the

TABLE II. Characteristics of methods of measuring galactic magnetic fields.

Observation	Location of effect	Predominant field orientation to line of sight	Estimated field (gauss)	Other influencing unknowns
Polarization of starlight	Along path	$\perp$	10^{-5} to 10^{-7}	Size, composition of grains
Nonthermal radio emission	At source	$\perp$	10^{-5}	Electron energy spectrum, field orientation
Polarization of non-thermal background	At source Along path	$\perp$ $\parallel$	10^{-5}	Distance of emitting regions
Faraday rotation of sources	Along path	$\parallel$	10^{-3} to 10^{-8}	Electron density, field orientation, path length
Zeeman effect	At source	$\parallel$	10^{-5} to 10^{-6}	Relation of individual cloud to general field

source. Some depolarization certainly could occur within the source from internal differential Faraday rotation or variation in the electron energy spectrum.

There is one method for measuring the magnetic field which does not depend on other unknown factors. That is the observation of the Zeeman splitting of the neutral hydrogen line at 21-cm wavelength. The presence of a magnetic field with a component along the observer's line of sight within a cloud of hydrogen causes the radiation from the cloud to be split into two components circularly polarized in opposite senses and with a separation in frequency of 2.8 cps per 10^{-6} G. This is an extremely small separation and very difficult to measure. The best hope is to find a hydrogen profile which is broadened as little as possible by Doppler effects and to look for a difference in intensity in the two senses of polarization. The sharpest lines to be found are in the absorption spectra of discrete sources and even they are about 10 to 20 kc/sec wide. Weinreb (1962), in his description of an attempt at measuring the field in this way describes the procedure in terms of the difference profile which is obtained when the signals received at the two different polarizations are compared. This difference profile, $\Delta T(f)$ is related to the observed (either polarization) profile $T(f)$ by the following relation, which holds if the frequency splitting Δf is small compared with the width of the observed line:

$$\Delta T(f) = \Delta f T'(f) = 2.8 \times 10^6 B_{11} T'(f),$$

where B_{11} is the line of sight component of the magnetic field and the prime denotes derivative with respect to frequency. Thus, only the profiles showing a steep slope at the edges have any hope of yielding a measurable Zeeman splitting. The method is therefore very limited in the sense that only a few clouds, at the present time at least, can be considered. The danger is that these clouds may not be typical of the general situation. They may happen to have a significant amount of the field directed away from the line of sight, and individual small clouds may not be intimately connected in a magnetic sense with the more general background.

The difficulty of the measurement is reflected in the fact that the separate recent attempts at observing the splitting are in disagreement. Davies reports the measurement of a field of 1.4×10^{-5} G in the spectrum of the Crab nebula (1964), while Weinreb (1962) and Morris, Clark, and Wilson (1963) each indicate that the upper limit for the field is approximately 5×10^{-6}. Most recently Verschuur (1965) has described measurements which lead to a field of less than 10^{-6} G in this source. The situation is complicated by the fact that the line in this source is complex in structure due to the presence of unresolved clouds, and the interpretation is therefore somewhat ambiguous. In the case of the spectrum of Cas A, the authors all agree that the field has an upper limit 10^{-6} G. It is thus apparent that a significant improvement in instrumental techniques is likely to produce a very important result; that is, a decision between 10^{-5} and 10^{-6} as the order of magnitude of the field. It is possible that the OH lines at 18-cm wavelength offer as least as good a chance to observe the Zeeman effect. The line is intrinsically narrower because of the larger mass of the molecule, and in fact some very narrow emission lines have been observed in the direction of several distant thermal sources. The separation of Zeeman components should be about the same as in hydrogen, so that we may be able to observe the magnetic field in two different sorts of areas in the galaxy, near or in HII regions, and in the cold, undisturbed general medium. This hope is contingent upon our understanding of the mechanism producing the very peculiar OH results, and the enormity of that problem will be indicated in the last section.

Table II gives a summary of our sources of information about the galactic magnetic field. Column 4, which gives values for the strength of the field estimated from each method, suggests strongly that the degree of influence of the magnetic field on interstellar conditions remains virtually unknown.

V. FORMATION OF INTERSTELLAR MOLECULES

The existence of molecules in the interstellar medium was realized in the early 1940's (McKellar 1941). Three constituents were apparent from the optical absorption lines: CH, CH+, and CN (see Table I). In 1963 the first non-carbon molecule, OH, was detected in the interstellar medium by its microwave transition at 18 cm (Weinreb, Barrett, Meeks, Henry 1963). Several attempts to find the OH optical transitions (Gaustad and van Woerden 1966, Goss and Spinrad 1966) at 3080 Å, have not, however, been successful, due to the opacity of the earth's atmosphere at this wavelength and to a low transition probability for the optical transition. The interstellar nature of CH, CH^+, and CN was shown conclusively by the observations of Adams (1949), thus dispelling earlier suggestions by Merrill (1946) that the lines are circumstellar. Adams showed that the velocities of the molecular features generally agree with those found for the atomic interstellar lines. Furthermore, Bates and Spitzer (1951) have shown that the intensities of the molecular lines are usually correlated with interstellar extinction. (Later on we will mention the one exception to this correlation.)

With several important exceptions all of the molecular lines arise from ground levels. This is caused by the fact that the kinetic temperatures in H I regions are so low that collisional excitations above the ground level are not important. The exceptions are two lines of CN which originate in a rotational level 4 cm^{-1} above ground level; the relative strengths of these lines correspond to a rotational temperature of $\sim 3°K$. The possible cosmological significance of this result has recently been pointed out by Field, Herbig, and Hitchcock (1965), who propose that the radiation temperature of the interstellar radiation field at 2.54 mm (the wavelength corresponding to 4 cm^{-1}) is $\sim 3°K$. (See Penzias and Wilson 1965, and Dicke, Peebles, Roll, and Wilkinson 1965 for a discussion of this problem.)

The observations of molecules present three fundamental problems: (1) The continual formation of molecules in the interstellar medium must be explained since the molecules are rapidly dissociated by the interstellar radiation field. (The mean life of CH against dissociation is 4×10^3 years—a short time compared with the age of the Galaxy.) Thus, we cannot say that the molecules are left over from some primeval stage of the Galaxy. (2) The observations indicate immense variation in intensity with position and also with respect to the atomic interstellar lines. In some cases, CH is stronger, in other cases CH^+. Furthermore, in a few striking examples, CN is much stronger than the other molecular lines. (3) Finally, we are faced with a fundamental problem of the interstellar medium: In which direction does the interstellar medium evolve? Does it go from simple entities (atoms, diatomic molecules) to complicated forms (polyatomic molecules, grains) or *vice versa*? Obviously, the three questions are not independent; in particular (1) and (3) may well be closely interconnected. Since our understanding of (2) and (3) is quite limited, we will discuss in some detail the problem of molecule formation in relation to CH, CH^+, CN, and OH—the molecules which are observed.

Three methods for forming diatomic molecules have been considered: (1) radiative association, (2) formation on grains, and (3) formation from polyatomic molecules. Radiative association was the first method proposed (Swings 1941, Kramers and ter Haar 1946). The excess energy of the colliding pair of atoms must be carried off by the emission of a photon since the collision of three atoms in the interstellar medium would occur at a rate of 10^{-24} yr^{-1} cm^{-3} and could only account for a negligible number of molecules. Thus, two-body radiative association is efficient only for molecules which satisfy two conditions: (1) an excited electronic state of the molecule must arise from ground-state atoms (the incoming atoms will be in the ground-state) and (2) a permitted transition must connect the above excited state with the ground state in order to rid the molecule of the excess energy. H_2 violates condition (2) while OH violates condition (1); CH, CH^+, and CN satisfy both conditions.

Bates and Spitzer (1951) have attempted to explain the observed densities of CH and CH^+ by means of radiative association. They consider practically all possible reactions governing the abundances of CH and CH^+: radiative association leading to CH and CH^+, photodissociation, photoionization, recombination ($CH^+ + e \to CH + h\nu$) and dissociative recombination ($CH^+ + e \to C + H$). (They neglect exothermic chemical exchange reactions of the form $CH + H \to C + H_2$. The rate coefficients for these reactions are much smaller than the other processes, however.) The values for the various rate coefficients involve the transition probabilities, the value of the radiation density at the dissociation and ionization limits, and various cross sections. Some of these values are known rather well and others can only be estimated. In particular, the rate constant for dissociative recombination is completely unknown. Bates and Spitzer then calculate the expected number densities of CH and CH^+ within a cloud. They concluded that the observed densities are about 100 times the values predicted by their theory; of the order of 10^3 H atoms cm^{-3} would be required in their theory to give the observed densities of CH and CH^+. This value is one to two orders of magnitude greater than the observed cloud density.

Radiative association is an inherently inefficient process as the following rough example indicates: the time for the two atoms to travel the intranuclear distance is about 10^{-14} sec. The half-life of the transition from the excited electronic state to the ground level is about 10^{-8} sec. Hence, the probability of a radiative capture is $10^{-14}/10^{-8}=10^{-6}$. Another major problem is that the molecules are dissociated quite rapidly by the interstellar radiation field—the $1/e$ time for the destruction of CH is 4×10^3 years.

The radiative association process has not been applied to the formation of CN—primarily since CN^+ is not observed. This latter fact in itself argues against the radiative association, since CN^+ would be expected in analogy to CH^+. [Since $n(C^+)/n(C) \sim 10^4 - 10^5$, $C^+ + N \rightarrow CN^+ + h\nu$, and $C^+ + H \rightarrow CH^+ + h\nu$ would be the predominant reactions followed by electron capture.] The major problem, however, for this test is that the ground state of CN^+ may not be the state determined experimentally by Douglas and Routly (1954) and tentatively assumed to be the ground state.

Before the 1963 observations of OH, the fact that all the observed free radicals (CH, CH^+, CN) could be formed by radiative association was taken as partial support for this method. The OH observations, along with the difficulties found by Bates and Spitzer force us to consider other formation mechanisms.

As an alternative, Bates and Spitzer (1951) suggested that the grains might be the third bodies which take up the excess in the kinetic energy. Details of this procedure have been dealt with by McCrea and McNally (1960), McNally (1962), and Gould and Salpeter (1963). Since the grain properties enter into these considerations, a model for the interstellar dust must be adopted. The dielectric grain theory has usually been used. An obvious logical difficulty is immediately encountered: in the dielectric grain theory, diatomic molecules are the basis of the condensation process. On the other hand, we need to invoke grains in order to explain the densities of CH and CH^+. No suitable solution to this paradox has been proposed.

The proposed method of forming CH and CH^+ is as follows (McNally 1962): the grain has a slight negative charge, as we have pointed out. Since most of the interstellar carbon is C^+, the collision cross section of the carbon gas with the grains is increased by an order of magnitude. Although H evaporates rapidly from the grain at a $T_g \sim 15°K$, the outside of the grain is thought to be covered with a layer of H atoms due to the great number of collisions of H atoms with the grains. McNally proposes that a C^+ ion hits the grain, neutralizes, and forms CH—the excess energy being taken up by the grain. Since the binding energy between molecules and solids is less than that between atoms and solids and since energy (3–4 eV) is liberated in the formation of CH, the molecule is freed from the grain surface and injected into the interstellar medium. CH^+ is subsequently formed by photoionization of CH. In computing the rate coefficient for this formation process, McNally uses the dielectric grain model of van de Hulst. The most uncertain parameter is $\bar{\omega}$—the probability that an atom of C striking the grain will leave as part of a molecule. McNally quotes experimental and theoretical evidence which indicates that this probability is approximately unity. There is, however, a great deal of uncertainty on this point. The final rate coefficient γ[number of CH molecules formed per cm^3 per sec$=\gamma n(C)n(H)$] is found to be 1.6×10^{-16} cm^3 sec^{-1}—approximately two orders of magnitude greater than the value for radiative association. McNally then sets up the equations of equilbrium for CH and CH^+, using the various processes of dissociation and ionization considered by Bates and Spitzer. Finally, he computes $n(CH)/n(H)$ for several assumed radiation fields in the interstellar medium. If the Lambrecht–Zimmerman field (see Sec. IB and Fig. 1) is correct, the above ratio is less than the observed value ($\sim 10^{-8}$) by an order of magnitude. If, however, the Lambrecht–Zimmerman field contains too much ultraviolet (as is expected), then the McNally theory can account for the observed number density of molecules.

As in the case of radiative association, the grain formation theory is not applicable to CN: an incident C atom has a very small probability of hitting a N atom ($[n(N)/n(H)]_{gas} \sim 10^{-4}$). Again, we cannot explain the fact that the density of CN is not negligible with respect to the density of CH.

The above theory is based on the dielectric grain model; if instead the graphite grain model is correct this could very well have important consequences for molecule formations. Indeed, pure graphite surfaces are not suitable for the formation of CH—graphite bombarded with neutral hydrogen will not yield CH; the carbon must be in gaseous form before formation can take place.

One further method for forming molecules has been proposed—the break-up of polyatomic molecules. Two methods of break-up have been proposed: (1) the ejection of polyatomic molecules from cool stars and the subsequent formation of diatomic molecules by the interstellar radiation field, and (2) the break-up of grains by low-energy cosmic rays or by evaporation near hot stars. Tsuji (1964) proposes that cool, luminous stars, which are known to eject mass at the rate of $\sim 10^{-6}$ solar masses per year, eject polyatomic molecules such as C_2H_2, CH_4, HCN, H_2O, NH_3, etc. After interaction with the interstellar radiation field, the observed free radicals are produced.

Process (2) was initially proposed by Bates and Spitzer to explain the observations of CH^+ in the Pleiades. The interstellar CH^+ lines seen in the late B type (fairly luminous) stars in this cluster are very strong with respect to other molecular and atomic lines. Two further peculiarities are found: (1) the number of molecules per cm^2 in the line of sight is not correlated with extinction in the cluster and (2) the velocities in all cases of the CH^+ molecule are such that the relative motion is in the sense of the star moving towards the gas. (The Pleiades are not unique, however; other unreddened B stars have CH^+ lines which are strong with respect to atomic lines.) To explain these unusual circumstances, Bates and Spitzer proposed that sublimation of solid CH_4 takes place from the grains; then the CH_4 is broken down in steps by the intense radiation field and subsequently passes through the CH^+

stage. The CH molecule is not seen since the radiative dissociation and ionization rates of CH near a star with a surface temperature of $\sim 2\times 10^4$ °K are much more rapid than CH^+. As the star moves into an interstellar cloud (the single cloud will produce a very small amount of extinction), the CH_4 begins to sublime as the grain temperature reaches 30°K. After the formation of the CH^+, this molecule is dissociated by the radiation field of the star. A hemispherical shell (centered on the star) of CH^+ is thus formed; the CH^+ that originally existed on the other side of the shell (i.e., behind the star as it moved through the cloud) has been dissociated by the radiation field of the star. This explains the fact that the CH^+ is found to be always moving towards the star. Again, this method is not successful in explaining the presence of interstellar CN which is occasionally seen in absorption in the late B stars. C_2N_2, if it exists in the grains at all, sublimates at $\sim$100°K—a much higher temperature than the CH_4 value (Herbig 1963).

Based on the high density of cosmic rays in the region 1–100 MeV (the suprathermal particles) proposed by Hayakawa (1960), Kimura (1962) and Takayanagi (1964) have proposed that diatomic molecules are produced by the interaction of these cosmic rays with the interstellar grains. They propose that the H_2O, CH_4, NH_3 molecules in the grains are broken down by the cosmic rays into OH, CH, CH^+, H_2, NH, CN, etc. This method can be efficient in forming molecules only if many radicals are formed for each incident proton. This method suffers from our ignorance of the suprathermal particle density; the existence of these particles is, indeed, not substantiated. However, one advantage to this method is that $n(\mathrm{CN})/n(\mathrm{CH})$ would be $\sim[n(\mathrm{N})/n(\mathrm{H})]_{\mathrm{dust}}$ (about 0.1 if the grains are dielectric) and not $[n(\mathrm{N})/n(\mathrm{H})]_{\mathrm{gas}}$ ($\sim 10^{-4}$). As we have seen, the previous methods of molecule formation cannot explain the observed numbers of CN molecules.

In the discussion of interstellar grains, we noticed several cases where anomalous phenomena are associated with HII regions. Recently, observations of CN at 3875 A and of OH at 18 cm in the microwave spectrum have shown peculiarities which seem to be associated with HII regions. The OH observations will be described in a later section. The anomalous excitation mechanism found in some of the OH observations operates only in the direction of the HII regions. At present no quantitative theory regarding the formation of OH is available. As we have seen, radiative association cannot account for the formation of OH. The scanty evidence available at this time indicates that the OH is formed near or inside the HII region. Might it not be that the OH is formed when dielectric or ice mantles of H_2O, CH_4, NH_3 grains are sputtered by colliding atoms?

The hydroxyl radical is not unique in showing peculiarities near HII regions. Münch (1964) has found two HII regions (NGC 7822 and IC 1396) whose exciting O stars contain very strong interstellar CN lines which are an order of magnitude stronger than any which had previously been detected. In NGC 7822, three of the associated O stars have CN lines besides CH and Ca^+ lines. One of the stars has a He° absorption line which arises inside the nebula. The velocities of the He°, CN, and CH are approximately equal. (It is possible, however, that there is a small difference in the velocities of the CH and CN lines, suggesting that the two molecules are not coexistent.) The Ca^+ lines usually originate in regions roughly midway between the sun and the background star; this appears to be the case in NGC 7822 since the Ca^+ lines differ in velocity from the molecular lines by 3–4 km/sec. On this basis, Münch has proposed that the CN molecules arise in rich dust complexes in the immediate neighborhood of the HII region—they are somehow related to the interaction process between the HII and HI regions. The Bates–Spitzer hypothesis for sublimation is not applicable to CN since C_2N_2 is probably not a major constituent of the grains. Münch has instead proposed that CN is formed as the grains are "flashed" by an ionization-pressure front advancing into the cool HI region from the HII region. This interesting proposal should be tested by laboratory experiments.

In the above considerations, we have only dealt with the formation of the four molecules which are observed in the interstellar medium. Several authors have also suggested the presence of H_2 in the interstellar medium. Unfortunately, the presence of H_2 cannot be ascertained from the earth's surface–the ultraviolet and far infrared contain the strong lines of H_2. The amount of H_2 is important in two respects: (1) The amount of molecular hydrogen may be a substantial component of the interstellar gas. (2) H_2 is an effective cooling agent, as we have pointed out elsewhere. Thus, the percentage of molecular hydrogen must be known to determine cooling rates in HI regions.

The direct radiative association of two hydrogen atoms in the ground state to form H_2 is a very improbable process since the photon emitted arises from a forbidden transition between $^3\Sigma$ and $^1\Sigma$ states. Thus, various authors (Kahn 1955b, McCrea and McNally 1960, Gould and Salpeter 1963, Gould, Gold, and Salpeter 1963) have considered the formation of H_2 on the surfaces of the interstellar grains in the manner which we have described above. Kahn, using the harmonic mean temperature of approximately 100°K and the fact that cloud–cloud collisions heat up the clouds to $3\text{–}4\times 10^3$ °K once in 10^7 years, proposed that 0.5% of the hydrogen present is in molecular form in order to give the proper cooling rate. The Gould *et al.* papers treat in considerable detail the formation and dissociation of H_2—they start from first principles and attempt to predict the density of H_2. The formation on grains is found to have a characteristic time of $\sim 10^8$ years. They also propose that dissociation of the H_2 takes place in encounters of gas clouds with the Strömgren spheres of O and B stars with a characteristic time of $\sim 10^8$ years. On this basis they propose that the equilibrium ratio of the densities of H_2 to H is in the range 0.1 to 10. A density of H_2 in this range will insure that molecular hydrogen is a major cooling agent in the HI regions. [However, van der Meyderberg, Knapp, Beenakker, and van de Hulst (1965) have reconsidered the formation of H_2 on grains and find that the process is much more inefficient than proposed by Gould *et al.* Clearly, additional work is needed to clarify these points.] The observations of H_2 will indeed be a significant breakthrough in our knowledge of the interstellar medium.

We have seen that the observations of molecules from one region to another are far from uniform. It seems quite reasonable to suppose that different formation processes would operate depending on the local conditions. However, many more observations and theoretical studies will be needed before we are capable of presenting a unified picture of molecule formation in the interstellar medium.

VI. RECENT OBSERVATIONS OF OH

The hope that another constituent of the interstellar gas could be studied in the microwave spectrum arose immediately after the discovery of the 21-cm hydrogen line. The search for the 18-cm lines of the OH radical was begun within five years after the discovery of the hydrogen line (Barrett and Lilley 1957). In the fall of 1963 two of the four lines in the multiplet formed by Λ doubling (hyperfine structure splits each of the Λ doublets) in the ground state were discovered as absorption lines in the spectrum of the strong radio source Cas A (Weinreb, Barrett, Meeks, and Henry 1963). These four lines occur at 1720, 1667, 1665, and 1612 Mc/sec with an expected intensity ratio of 1:9:5:1 (see Fig. 10) so that it is not surprising that 1667 and 1665 were observed first. The developments since this discovery have been extremely rapid and have led to such a new view of processes in the interstellar medium that, despite the great danger of this review's being outdated before it is printed, we wish to conclude with this current report on the developments.

The particular usefulness of OH in a study of the interstellar gas arises from several factors. One is the obvious measure of the abundance of oxygen compared to hydrogen. Another is the different molecular weight which, under certain conditions, allows separation of thermal and turbulent effects in line broadening (as described in Sec. IIB). From the point of view of excitation conditions in the interstellar medium, OH is an invaluable tool—on well-known grounds and on newly discovered ones. The former relate to the fact that the OH excitation mechanism is quite different from that of hydrogen. The excitation of the hyperfine line in the hydrogen spectrum is collisional, and the excitation temperature is therefore the kinetic temperature (Purcell and Field 1956). The excitation of the OH lines is not collisional, due to the fact that they arise from electric dipole transitions with much higher transition probabilities than the magnetic dipole transition producing the 21-cm hydrogen line. The excitation temperature of these lines is therefore more closely coupled to the radiation temperature in the medium. This fact led to the search for OH first in absorption, since the radiation temperature is certain to be very low in HI regions. More recent observations have suggested the existence of a totally unexpected excitation mechanism for the OH radical, the complexity of which defies theoretical explanation at the present time. The early observations did not suggest such peculiarities, for in the spectrum of Cas A the lines at 1667 and 1665 Mc/sec were both observed, in about the expected intensity ratio of 9 to 5. In addition, each of the components of the multiplet was split into several lines because of the presence of several clouds of OH along the line of sight each with its differential Doppler shift. Each of these clouds could be directly associated with similar HI clouds which had been observed long before in the spectrum of Cas A.

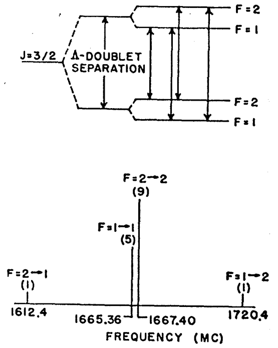

FIG. 10. The complete energy level diagram for the $^2\Pi_{3/2}$, $J=\frac{3}{2}$ ground level of OH showing the hyperfine structure and the related microwave spectrum with theoretical relative intensities indicated in parentheses.

Following the discovery of OH in Cas A, it was found also by several groups in the spectrum of Sgr A, the source at the galactic center. The situation there was not so simple. The line was at first reported to have an optical depth of a few percent and to have a velocity nearly the same as the velocity of an HI cloud in this direction (nearly at rest with respect to the sun). The Australian group (Robinson, Gardner, van Damme, and Bolton 1964) was the first one to find that the line which had previously been observed was actually only a small dip on the side of an enormous feature with optical depth of 0.9 and width of 50 km/sec centered at a frequency corresponding to a Doppler shift of +40 km/sec. The group at Harvard (Goldstein, Gundermann, Penzias, and Lilley 1964) subsequently found a similar line displaced to negative velocity (at

−120 km/sec). Thus, as shown in Fig. 11 (Williams 1965), the principal components of the OH spectrum in Sgr A were a complete surprise and bore no relation to the HI observed in this direction. In addition, the great width of the lines indicated tremendous internal motions in the clouds, internal motions quite unknown in any HI observations and certainly unexpected in OH. Why should large concentrations of a molecule occur where such violent motions were going on, where conditions would appear so unfavorable for molecular formation? The concentration of OH molecules is nevertheless very large, as shown by the line ratios. All four lines of the multiplet were observed, but not in the predicted ratio of intensity; that is, they appear in the ratio 1:2.7:2.2:1 rather than 1:9:5:1. These anomalous intensities could be attributed to an effect long known by astronomers in their study of stellar atmospheres—that is, the variation of the intensity ratio in a multiplet due to great optical depth and the saturation of one or more of the lines, the so-called "curve-of-growth" effect. (See also McGee, Robinson, Gardner, and Bolton 1965).

The next important contribution was the observation of OH absorption in regions near the direction of the galactic center, but not at the position of Sgr A. The galactic background continuum radiation is strong enough in these regions to permit observation of OH in absorption. This observation provides several very important additions to our store of knowledge of OH. The important factor is that the background source is an extended one, many degrees in extent. Thus, it provides an opportunity to study the angular distribution of the radiation and to make models of the structure of a great complex of OH clouds. The region is full of broad, high velocity components bearing little or no relation to the HI observations in the same directions. The extended background makes possible another conclusion because the source fills the beam of the antenna. In this case the measured antenna temperature at frequencies outside the OH line is equal to the brightness temperature of the continuum background at these frequencies. Since the OH appears in absorption, it must be cooler than the background, which has a brightness temperature of about 10°K. By cooler, of course, we mean a lower excitation temperature of the molecule, which is not the kinetic temperature, but is the factor which determines the population of the levels in the molecule and, hence, its absorbing properties.

This discovery of a 10° limit on the excitation temperature was something of a blow to the search for OH in emission. If the excitation temperature were, indeed, so low, the chances of finding the line in emission would be very small. It should be remembered that in the case of absorption the measured brightness temperature for a fixed amount of material depends on the temperature of the background source, and in the case of emission it depends on the excitation temperature of the material. This decrease in the chance of finding OH in emission was also a blow to the hope that OH would become an important tool in studying the interstellar medium. If its study were limited to absorption lines in the spectra of a few bright sources, to be seen at only isolated places in the sky, its usefulness would certainly be limited. Searches for OH in emission were nevertheless carried out in all the likely places: in the anticenter, in the midst of dark clouds of dust, and at random places in the galactic plane, all without notable success.

With the advent of improved receivers, attempts to find OH absorption in weaker sources were begun. It was not found in the next three brightest sources, the Crab Nebula, the Orion Nebula, and Cyg A. The next most likely candidates at this frequency were to be found in the Westerhout catalogue of radio sources at 1390 Mc/sec (Westerhout 1958). These sources are largely thermal emitters, and mostly identified with optically observed HII regions, clouds of gas radiating in the radio region by free–free emission (*bremstrahlung*) of electrons at a temperature of about 10^4 °K. They have an advantage from the observational point of view in that they are relatively extended in angular size, of the order of a degree. Rather quickly a few of these sources were found to have measurable absorption lines at 1667 Mc/sec, the strongest line of the multiplet (Williams 1965). The search was then extended to fainter continuum sources, in particular to the source W49. This is a relatively bright thermal source at this frequency but shows no optical radiation whatever. The region does, however, have many heavy obscuring clouds which probably hide from our view a large HII region beyond. The dust does not obscure the radio radiation, and so we observe a bright thermal radio source. The first observations of this source provided the greatest surprise since the discovery of OH (Weaver, Williams, Dieter, and Lum 1965). The 1667-Mc/sec line was not in absorption *but in emission*! These observations were made with an instrumental resolution of 10 kc/sec, or about 2 km/sec. Very considerable structure was visible in the profile and indicated that still greater resolution would be desirable. The next step was observation with 2-kc/sec resolution (0.4 km/sec). The profile was indeed further resolved and showed lines as narrow as 1 km/sec and antenna temperatures as high as 9°K, as shown in Fig. 12. Therefore, the excitation temperature of OH near this HII region must be higher than in regions of the galaxy far from the sources of intense radiation. But still further surprises lay in store. The profile of the 1665 Mc/sec line in the same source did indeed have components resembling what was expected (several clouds rather like the 1667-Mc/sec ones with reduced intensity), but the surprise was that at a place in the spectrum where only a small amount of 1667-Mc/sec radiation appeared there were several very strong, sharp peaks of emission at 1665 Mc/sec. They were, in fact, as bright as 20° and as narrow as 0.4 km/sec—

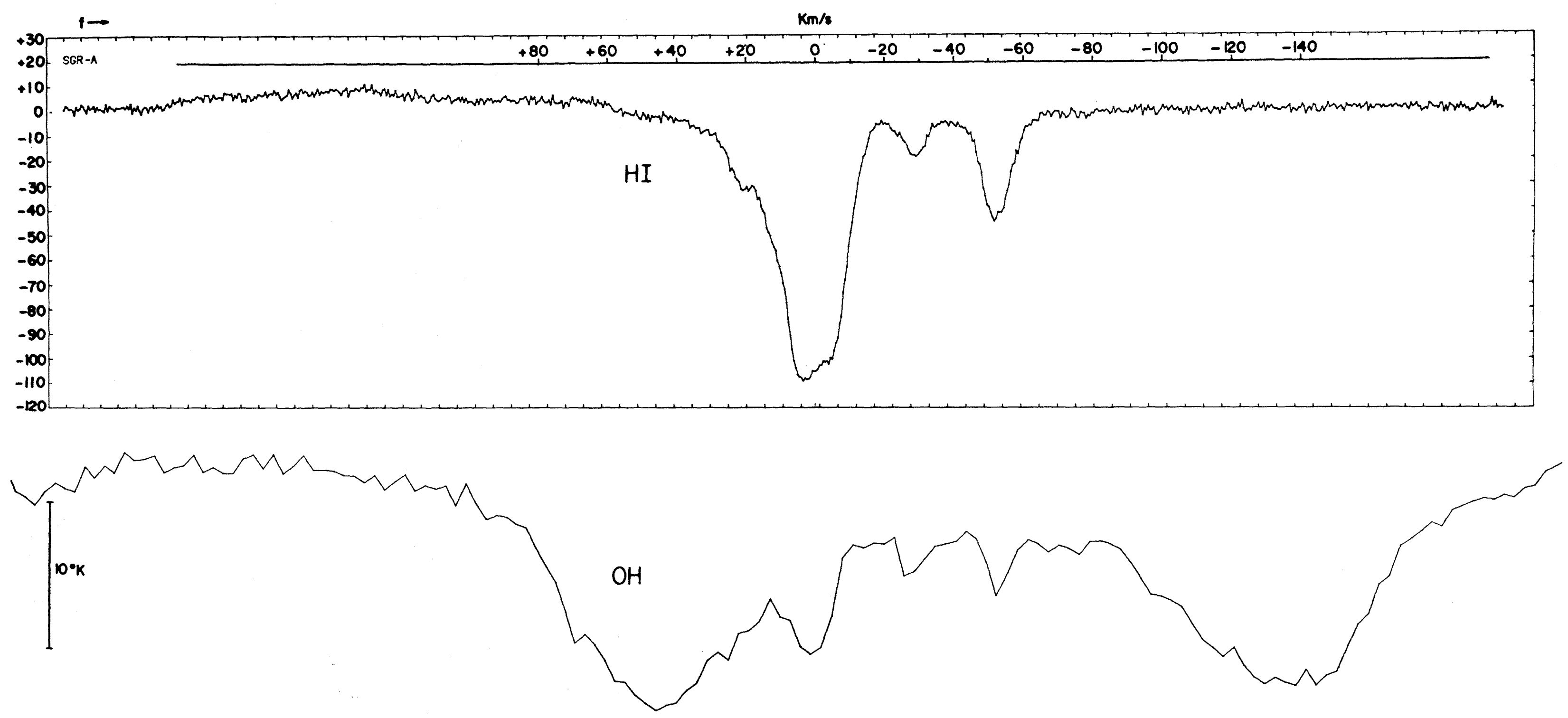

FIG. 11. Profiles of HII and OH (1667 Mc/sec) in the direction of the galactic center (Williams 1965). Velocities are with respect to the local standard of rest, the average velocity in the vicinity of the sun.

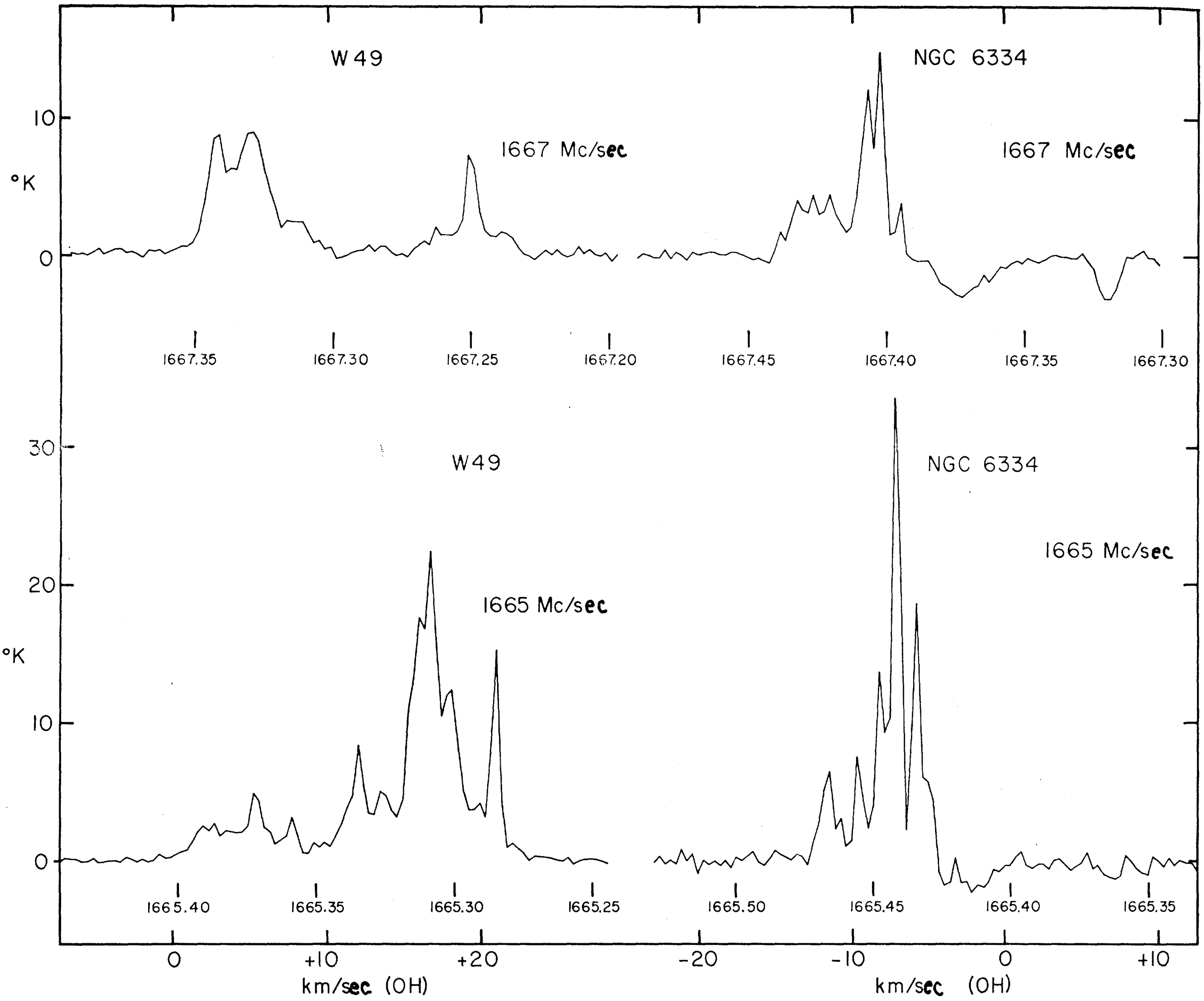

Fig. 12. Spectra of W49 and NGC 6334 in the OH lines with a resolution of 2 kc/sec (0.4 km/sec) (Weaver, Williams, Dieter, and Lum 1965).

the emission in 1665 *exceeded* that in 1667, *not* fell below it, as we would predict if it arose according to normal expectation for the OH multiplet. (This has been confirmed by Zuckerman, Lilley, and Penfield 1965.)

It was immediately obvious that this observation could not be explained in a simple fashion. Any ratio of intensities of 1665/1667 up to one can be explained on the grounds of high optical depth. If the stronger line is saturated, the apparent ratio can be as high as one. In no such way, however, can the ratio exceed one. In W49 the intensity in some of the components of the 1665 line profile are near 20° and the corresponding 1667 components are not detectable.

In some ways the source W49 is not an ideal one for investigating the problem. For one thing, the spectrum in the region of interest is enormously complicated; that is, there are apparently many isolated clouds of gas along the line of sight which make direct comparison of the two transitions rather complicated. If, for example, one wants to determine just how much extra radiation there is at 1665 Mc/sec, one needs to subtract from the observed profile at that frequency an amount which is some fraction of the intensity at 1667, but just what fraction between 1.0 and 1.8 is not clear. In addition, W49 is quite invisible optically and hence nothing is known about its other properties. The radio source is quite small in angular size so that with the relatively small antenna used, it is not possible to tell from where in the nebula the radiation comes. The Orion Nebula, on the other hand, is a bright nearby source and the HII region for which the most optical information is available. The first observations of Orion were made at the edges of this quite extended nebula on the theory that the molecules would probably be dissociated in the central part of such an enormously hot region. These observations showed no radiation at all at 1665 Mc/sec; but an observation made exactly in the direction of the center of the nebula and of the well-known thermal radio source Ori A yielded emission of several degrees antenna temperature. The profile again has several sharp velocity components, but in this case no confusion with 1667 Mc/sec. Ori A had been one of the first sources investigated for OH absorption, and had indeed been very thoroughly observed near 1667 Mc/sec, with consequent upper limits on optical depth of 0.005 (Robinson, Gardner, van Damme, and Bolton 1964). It is a curious quirk of fate that this emission line was not found long ago. Searches for OH were obviously carried out in the frequency of the strongest line of the multiplet; when no radiation in this range was found, there was clearly no point in looking at a weaker line. With the clue of W49, however, it was apparent that 1665 Mc/sec should from now on be investigated more or less independently of 1667.

A search for the anomalous OH emission in other HII regions was carried out since these observations suggested that something peculiar to these regions is influencing the radiation—for instance, the presence of large amounts of radiation either in the ultraviolet or at 18-cm wavelength. The search yielded several other sources: IC 1795 (W3), NGC 6334 (shown in Fig. 12), W51, and W75 (Weaver, Williams, Dieter, and Lum 1965). In these sources the line ratios were also completely unexplainable on the basis of the usual excitation mechanisms. Each of these sources showed rather broad absorption features as well as emission components which were remarkably narrow. The width of some of these emission features is that appropriate to the thermal Doppler broadening for a 13°K source with no turbulence. This is hardly consistent with the observed temperature (10^4 °K) or mass motions (5 or more km/sec) in HII regions. A further surprising result came from measurements at the Lincoln Laboratory of MIT (Weinreb, Meeks, Carter, Barrett, and Rogers 1965); the emission at 1665 Mc/sec from W3 is strongly linearly polarized. The several velocity components of the profile show different planes and different percentages of polarization. This result was confirmed at Berkeley and extended to other sources, especially NGC 6334, which shows a high degree of polarization at both 1667 and 1665 Mc/sec—greater than 35% (Williams, Dieter, and Weaver 1965). (One of the components shows 100% linear polarization.) Most recently Barrett and Rogers (1966) have detected, in addition, strong circular polarization in W3, Orion, NGC 6334, W49, and Sgr B_2.

Careful investigation of the radiation at 1612 Mc/sec and 1720 Mc/sec, the theoretically weaker lines of the multiplet, showed a complete divergence from prediction. The shape of thejprofile as measured in each of the lines appears to be quite independent of the others—that is, a given cloud does not seem to radiate in the same fashion at all four frequencies. In some sources there are broad features at 1612 and 1720, where narrow ones occur at the other frequencies; in others there are narrow features in one or the other of these lines at frequencies corresponding to Doppler shifts at which no radiation occurs at all in the "stronger" lines (Weaver, Williams, and Dieter 1965).

Continued observations presented observers with another surprise. The profile observed in NGC 6334 was not of constant shape at either 1667 or 1665 Mc/sec (Dieter, Weaver, and Williams 1965). For example, a peak in the 1665-Mc/sec profile decreased in intensity by a factor of three with respect to another peak in the same profile, in a period of two months. Investigation of the 1665—Mc/sec profile of the Orion Nebula showed that here also were secular variations—a decrease in one peak relative to another by a factor of 1.5 in a similar time interval. No such variation has ever been observed before in the interstellar medium.

All of these peculiarities have led to suggestions of rather exotic excitation mechanisms for the lines. No single one has as yet explained all the observations, and we shall only indicate roughly the current proposals. Reference to the energy level diagram in the ground state Fig. 10 may indicate some of the problems. Radiation at 1665 and 1612 Mc/sec arises from the same upper level so that any anomalous intensity produced solely by an overpopulation of this level should be reflected in both lines (the same is true for 1667 and 1720 Mc/sec). This overpopulation in conjunction with a source of radiation to provide stimulated emission from this level could produce peculiar line intensities and "artificially" narrow lines; in effect, a maser in the interstellar gas (Field, private communication). One of the central unsolved problems in this proposal is the question of how to overpopulate the $F=1$ level in the upper state with respect to $F=2$. They differ in energy by only about 1 μV. The high degree of polarization and the rapid variations in intensity also still elude any credible theoretical explanation.

The OH molecule, then, opens a new realm of speculation about conditions in the interstellar medium. Its fascinating properties lend new impetus to the search for other constituents of the interstellar gas which may be radiating in the microwave spectrum.

We have tried to describe the complex problems and the variety of attacks upon them in the study of the interstellar medium. Our intention was to describe the progress which has been made in building up a detailed physical description of this medium. The outcome has been a picture full of uncertainties, but one which gives the impression that the discovery of a few vital pieces of the puzzle will clarify it all. The search for these pieces is likely to be a fascinating pursuit.

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