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Evidence for a Large Population of Shocked Interstellar Clouds

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Abstract. A 21 cm absorption measurement over a long path length free of the effects of differential galactic rotation indicates the existence of two distinct cloud populations in the plane. One of them consisting of cold, dense clouds has been well studied before. The newly found hot clouds appear to be at least five times more numerous. They have a spin temperature of ~ 300 K, an rms velocity of ~ 35 km s^{-1}, twice the total mass, and hundred times the kinetic energy of the cold clouds. Over long path lengths, the hot clouds have $N_H/\text{kpc} \sim 2 \times 10^{21}$ cm^{-2} kpc^{-1}, and are estimated to have individual column densities $\leqslant 10^{20}$ cm^{-2}. We propose that they are shocked clouds found only within supernova bubbles and that the cold clouds are found in the regions in-between old remnants, immersed in an intercloud medium. We conclude that the solar neighbourhood must be located between old supernova remnants rather than within one.

Key words: 21 cm absorption—shocked clouds—spin temperature—high velocities

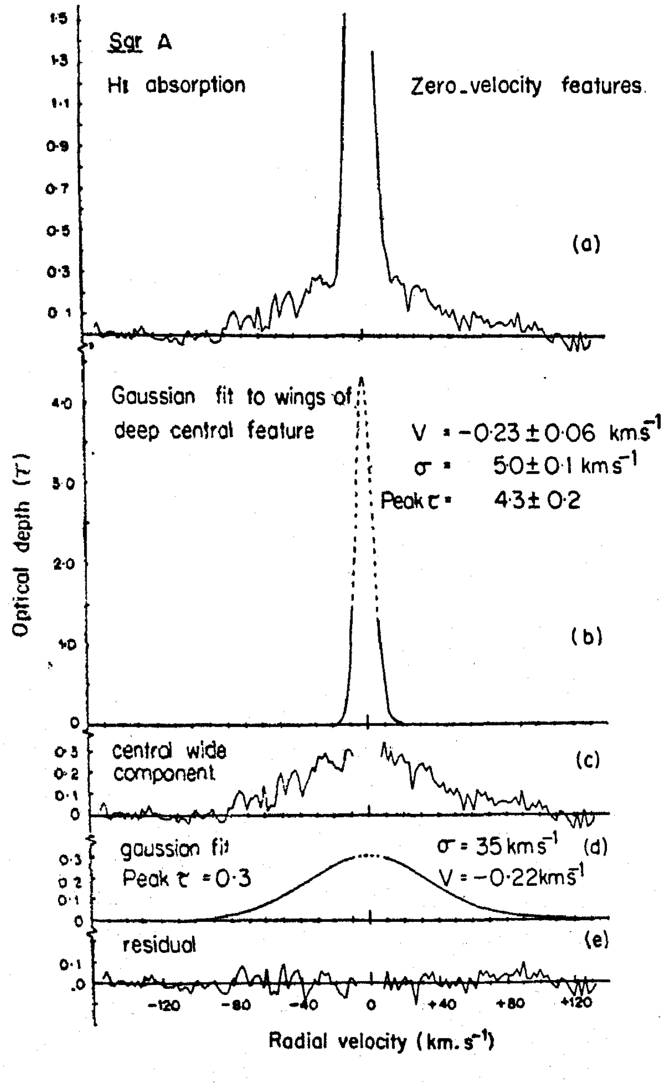
1. Introduction

A recent analysis (Radhakrishnan and Sarma 1980; hereafter Paper I) of the H I absorption spectrum of Sgr A obtained with the Parkes interferometer (Radhakrishnan *et al.* 1972a) has revealed, in addition to the other well known features, an unexpected, very wide, low optical depth feature, at zero velocity. According to these authors, the new feature represents an amount of neutral hydrogen in the Galaxy comparable to that in dense cold concentrations, and it contains most of the energy in mass motions of the interstellar gas. In this paper, we shall discuss and elaborate on these two statements and also present their implications for other studies of the interstellar medium.

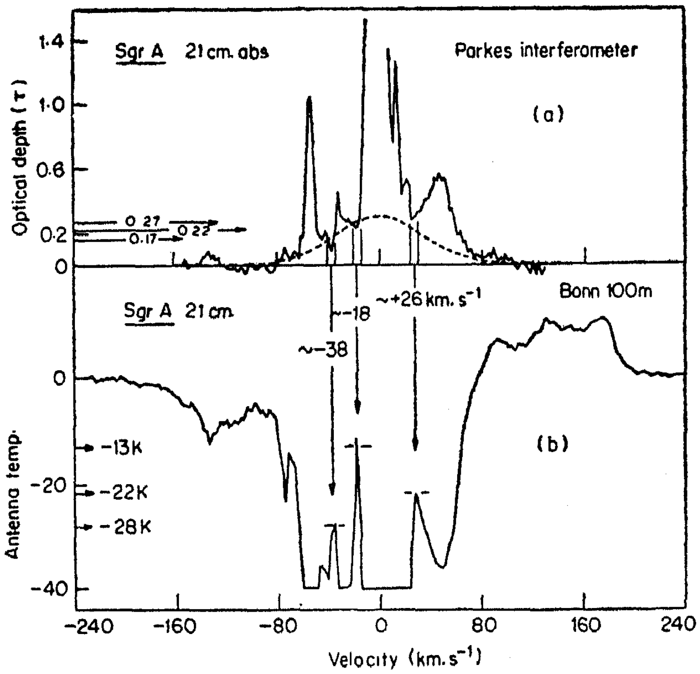
We reproduce in Fig. 1 that part of the profile from Paper I relevant to the present discussion. The narrow central feature, Fig. 1b, represents typical cold concentrations such as have been extensively studied in other directions in the Galaxy and whose properties have been described by Radhakrishnan and Goss (1972). It is the wide feature (Fig. 1d) whose interpretation is the main subject of the present discussion. We also list in Table 1, the parameters describing these two features that we shall use here. The spin temperature characterising the hydrogen in the wide features was only mentioned in Paper I as being a few hundred degrees kelvin. We give in Table 1 a more specific value obtained as described in the Appendix by a comparison of the interferometer measurement (Fig. 2a) with the single dish measurement of Sanders, Wrixon and Mebold (1977) (Fig. 2b).

Two additional parameters of interest that follow from Table 1 are the average values of number and energy densities of the hydrogen in the wide feature

$$\langle n_H \rangle \approx 0{\cdot}5 \text{ cm}^{-3}, \text{ and } (3/2)\, \rho \, \langle v^2 \rangle \approx 1{\cdot}5 \times 10^{-11} \text{ erg cm}^{-3}.$$



Figures 1a to e. Resolution of the zero velocity features a, in the H I absorption spectrum of Sgr A into two Gaussian b and d; the residuals c and e after subtraction of these components.



Figures 2a and b. The total HI optical depth profile obtained in the direction of Sgr A with the Parkes interferometer (from Paper I) **a**, and the antenna temperature profile obtained in the same direction with the Bonn 100 metre telescope (Sanders, Wrixon and Mebold 1977) **b**. See Appendix for discussion.

Table 1. Parameters of the Gaussian components fitted to the zero velocity features of the HI absorption spectrum of Sgr A (From Paper I).

Fig. No.	Velocity km s^{-1}	Peak τ	σ km s^{-1}	N_H/T_s 10^{19} cm^{-2} K^{-1}	T_s^* K	N_H 10^{21} cm^{-2}
1b	−0·23	4·3	5·0	9·8	80	8
1d	−0·22	0·3	35	4·9	300±50	15

*Taken from Radhakrishnan *et al.* (1972b) for the clouds in the narrow feature, and derived in the Appendix for the wide feature.

In the next section we shall identify the wide feature with low-optical-depth clouds distributed globally in the Galaxy; this is as opposed to a ' local ' origin, for example at the galactic centre. We shall then attempt to show that these clouds must have acquired their characteristics from collisions with the shock fronts of expanding supernova remnants. This will be followed by a discussion of the implications for some other theoretical and observational studies of the interstellar hydrogen; our conclusions will be summarised in the final section.

2. On the global origin of the wide feature

We shall repeat first the argument advanced in Paper I supporting a distributed origin for the wide feature (Fig. 1d), namely that the mean velocity was indistinguishably different from that of the narrow feature (Fig. 1b) and from zero. The spin temperature of the wide feature, ~ 300 K, implies for pressure balance, about a fourth of the number density of atoms found in cold clouds. This combined with the high column density of $\sim 15 \times 10^{21}$ cm^{-2} requires the gas to be distributed in a large number of clouds; a single concentration would be too massive. All the gas associated with the galactic centre is known, from various studies of this region, to have velocities differing significantly from zero. On the other hand, a large number of clouds, or cloudlets, each with its own peculiar motion, if distributed along the line of sight to the centre, could be reasonably expected to have a mean velocity of zero.

The next argument we offer is through a comparison with optical observations. One of the earliest studies of the motions of interstellar clouds was carried out by Blaauw (1952) who analysed the measurements of Adams (1949) to determine the distribution of radial motions. The observed blends were separated into individual components, and both an exponential and a Gaussian were tried as fits to the distribution of velocities (Fig. 3). Although he had noted that the intensity of the

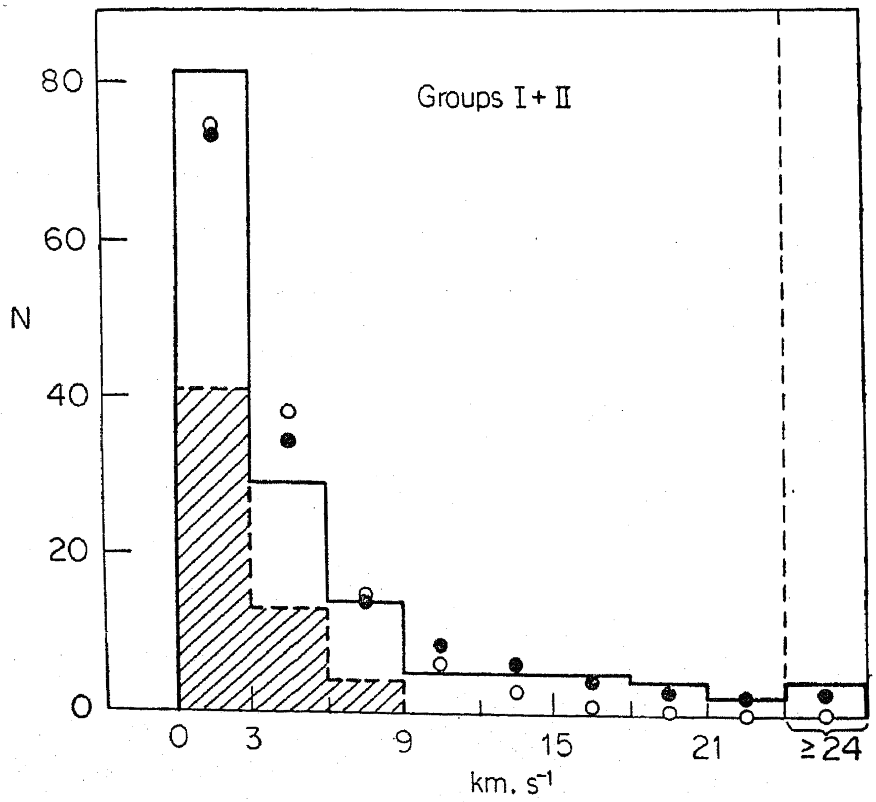


Figure 3. Reproduced from Blaauw (1952). Groups I+II represent stars whose distances were < 500 pc. The smooth curve represents the observed numbers of velocities in intervals of 3 km s^{-1} in groups I + II. The dashed curve represents the contribution due to the components with intensities > 6 in ADAMS' scale.

Circle : numbers computed on the basis of hypothesis A with $n=3$, $\sigma=5.5$ km s^{-1}.
Dots: numbers based on hypothesis B with $n = 3$, $\eta = 5.0$ km s^{-1}.

Ca II lines showed a correlation with velocity, in that those clouds with large peculiar velocities had weaker lines on the average, he did not attempt to separate them into two distributions. He concluded that the radial motions were satisfactorily described by a single exponential (Blaauw 1952).

An indication that there was more than one type of interstellar cloud (identifiable by its motion) was the correlation found by Routly and Spitzer (1952), of the ratio of sodium I to calcium II column densities with large peculiar velocities relative to the local standard of rest. The sodium-to-calcium ratio decreases with increasing velocity. This correlation was further investigated and confirmed by Siluk and Silk (1974) using more recent data for 64 stars. We show in Fig. 4a histogram constructed from the data in their paper of the velocities observed in the direction of these stars. The velocity range is much larger than in the sample of Blaauw (Fig. 3), and the histogram is much more suggestive of two distinct distributions, one of which can be well approximated by the Gaussian shown in Fig. 4. The other distribution is clearly seen to be a wide one, but its shape cannot be reliably determined because of the poor statistics of this sample.

We show in Fig. 5 a folded version of the optical depth plot of Fig. 1a, and the similarity between it and Figs 3 and 4 clearly suggests that the low wide H I absorption feature is due to the higher velocity clouds discussed above which show weak lines and a sodium I to calcium II anomaly. In comparing these figures it must be remembered that in the optical case it is the numbers of clouds with a given velocity that are being summed, whereas in the H I profile it is the optical depths that are being added together. It may be noted that the fluctuations in the wings of the wide H I feature (Fig. 1c) are somewhat greater than would be expected from noise, and suggest individual cloud-like contributions rather than say from a uniform diffuse medium. As the optical observations were made in many directions in the

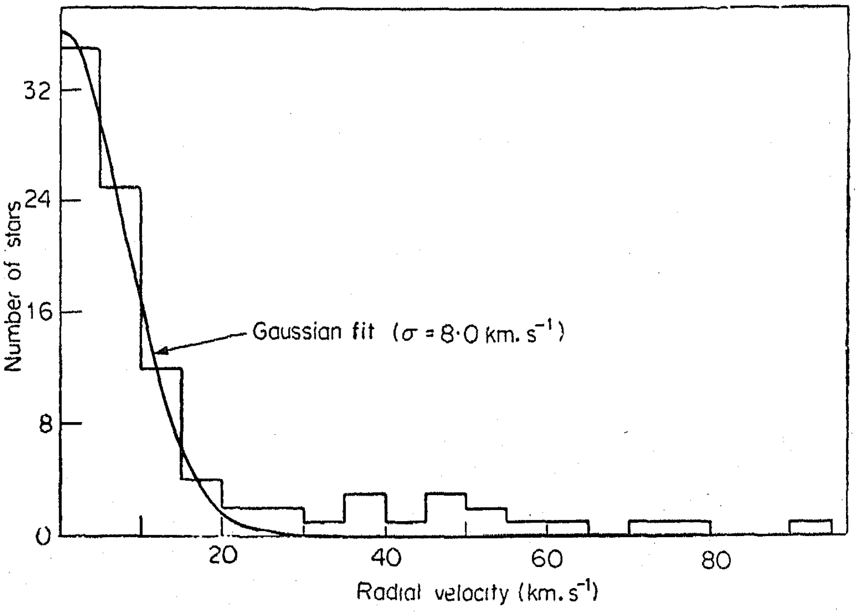


Figure 4. Histogram of radial velocities observed in the direction of 64 stars from the data in Siluk and Silk (1974). The low velocity features can be approximated well by the Gaussian shown. The higher velocity features are associated with anomalous ratios of sodium I to calcium II column densities.

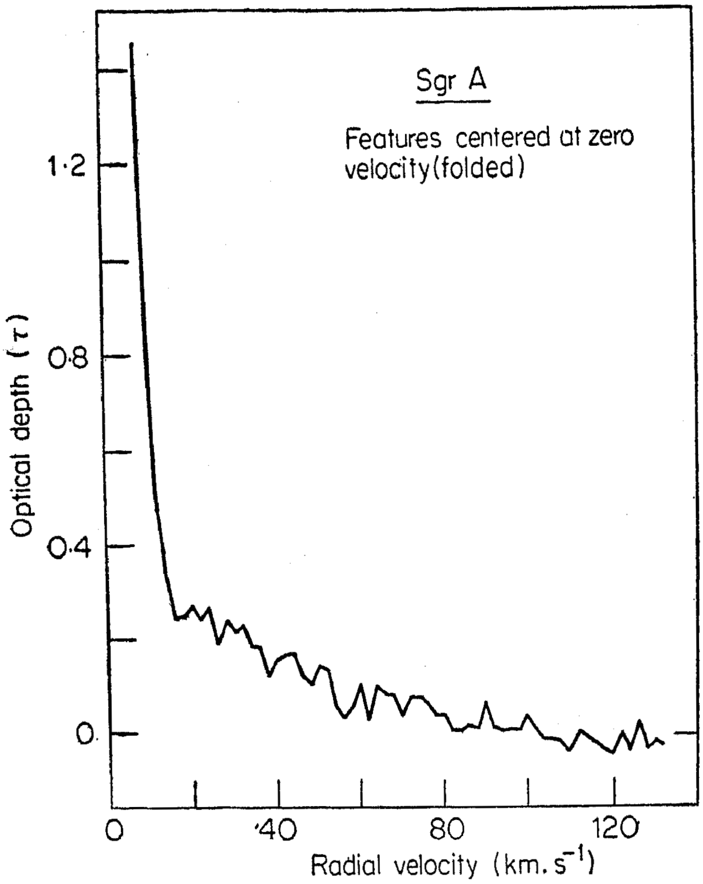


Figure 5. A folded version of the optical depth distribution of Fig. 1a. A similarity with the distributions of Figs 3 and 4 is evident, as also the presence of two distinct distributions.

Galaxy, the velocities are unconnected with motions near the galactic centre and are representative of all directions.

On the basis of an early study of H I absorption in a number of sources, Clark (1965) had already surmised that the narrower Gaussian distribution of cloud velocities obtained from 21 cm studies differed from the exponential found by Blaauw (1952) because the components at higher velocities were missed in the hydrogen study. A significant increase in the temperature of hydrogen clouds and the consequent decrease in their optical depths would make them harder to detect in absorption. On the other hand, the 21 cm *emission* from such optically thin clouds would be independent of temperature and therefore easily detectable A comparison of line velocities obtained both optically and at 21 cm led Heiles (1974) to note that optical absorption lines should perhaps be associated with emission rather than absorption lines obtained at 21 cm. Also Mast and Goldstein (1970), from a study of 21 cm emission features away from the plane, concluded that an exponential was a good fit for the velocity distribution they obtained. With hindsight, these two conclusions can be understood if there are also clouds at a higher temperature and with a lower column density (as we shall show presently) than those responsible for the typical 21 cm absorption lines. The reason that Mast and Goldstein (1970), as also Blaauw (1952), considered a single exponential an acceptable fit for the combined distribution was that it was limited in its velocity range ($\leqslant 30$ km s^{-1}). The higher velocity features, which were missed because they were weaker, would have brought to light the existence of two distinct distributions.

The mean temperature of the clouds making up the wide feature is 300 K$\pm$50 as shown in Table 1. Since the gas is optically thin, this value must truly represent the harmonic mean temperature of these clouds. There is undoubtedly a distribution of clouds with temperatures from somewhat below to presumably much higher than 300 K. But as the typical temperature for cold concentrations is of the order of 80 K, we see that the higher velocity clouds are definitely hotter by a factor of 4. If overall pressure equilibrium is invoked, the number density n_H in these clouds should be approximately four times less than in the cold clouds. If N_H (cold) and N_H (hot) are the typical column densities per cloud of each variety, then

$$\frac{N_H\ (\text{hot})}{N_H\,(\text{cold})} \approx \left(\frac{M\,(\text{hot})}{M\,(\text{cold})}\right)^{1/3} \left(\frac{T_{\text{hot}}}{T_{\text{cold}}}\right)^{-2/3}.$$

The dependence on the mass ratio is weak as we see, but as $T_{\text{hot}} \approx 4T_{\text{cold}}$, the optical lines should be weaker in the hot clouds by at least a factor $\sim 2{\cdot}5$. We estimate the hydrogen column densities to lie in the range $5\text{–}10\times 10^{19}$ cm^{-2}. For the 21 cm line however, the integral over velocity of the optical depth

$$\int \tau\, dv \propto \frac{N_H}{T_s}.$$

The ratio of the optical depths for equal masses is thus

$$\left(\frac{T_{\text{hot}}}{T_{\text{cold}}}\right)^{-5/3} \approx 1:10.$$

A lower mass, and increased turbulence, will be two additional factors that contribute to decreasing the *peak* optical depth of features due to hot clouds by over an order of magnitude from those of typical cold clouds.

There has been a longstanding difference in the number of clouds per kpc estimated from optical and radio measurements. Blaauw (1952) found 8–12 clouds per kpc while Radhakrishnan and Goss (1972) found only 2·5 per kpc even after allowing for various selection effects. Although the correction for instrumental blending applied by Blaauw has been criticised (see Heiles 1974), there is no question that there is a large difference in the numbers obtained. This serious discrepancy can now be understood in terms of the discussion in the previous paragraph, and is yet another argument supporting the picture presented above. If the majority of clouds along any given line of sight belong to the hotter and higher velocity category, they would have been below the sensitivity limit of the 21 cm survey on which the statistics were based.

Finally it may be noted that the total mass in such clouds is greater than in the lower velocity clouds. From Table 1 we see that the column density of the gas producing the wide feature is twice that of the gas represented in the narrow feature.

Assuming that this will be true over any long path length in the Galaxy, we are led to the conclusion that there is twice as much gas, and hence total mass, in the higher velocity clouds.

We wish to avoid confusion with the so-called high velocity clouds (HVC) and intermediate velocity clouds (IVC), referring to gas in differing velocity ranges and usually observed at *high latitudes*. We shall use the terms fast and/or hot in referring to the clouds we have just described, characterised by a $V_{\rm rms} \sim 35$ km s^{-1}, a $T_{\rm spin}$ of a few hundred degrees, and which are found in the *galactic plane*.

3. Association with supernova remnants

We have argued in the preceding section that the gas represented by the wide feature in the Sgr A profile consists of a large number of clouds characterised by a lower optical depth, a higher temperature and a higher velocity than typical cold clouds. They are more numerous, contain twice as much total mass, and are distributed as widely as the colder variety. If this picture is accepted, we shall now show that a connection with supernova remnants is inescapable.

The dominant role that supernova explosions must play in the dynamics of the interstellar gas has been stressed repeatedly by Spitzer (1956, 1968, 1978). That they must also play an important role in maintaining the heat balance was revealed by the Copernicus measurements. In addition to the discovery of the widespread coronal gas at temperatures close to a million degrees, and soft X-ray emission, it was possible to firmly establish that cosmic rays played little or no role in heating the interstellar gas (Williamson *et al.* 1974; Jenkins and Meloy 1974; York 1974; Spitzer and Jenkins 1975).

Several theoretical investigations in recent years have pointed out that the effects of supernova shocks must pervade most of galactic space. Cox and Smith (1974) proposed that the remnants would overlap each other and connect up in a network of tunnels filled with hot coronal gas. McKee and Ostriker (1977) have put forward the most comprehensive model yet for the interstellar medium in which three components are regulated by supernova explosions in an inhomogeneous substrate. In their model, as in other studies along the same lines (*e.g.* McKee, Cowie and Ostriker 1978) there is a natural and intimate connection between the heating of clouds and their acceleration as a whole. Earlier models while preoccupying themselves with temperatures, pressure equilibrium, etc. had said very little about the motions of the gas, because their heating mechanisms were independent of motions. In supernova models, on the other hand, clouds are accelerated by the same shock wave that also heats them up as they pass through it.

It has been recognised for many years that even to explain the motions of cold clouds with relatively low velocities, supernova energy was required as an input. Spitzer (1978) estimates that supernova shocks acting with 3 per cent efficiency can explain the observed cloud motions; he mentions specifically that the motions of 'high velocity clouds' have not been taken into account in his discussion. If all the spiral arm regions are pervaded by shock fronts, and if all standard-cloud motions and gas heating are to be attributed to them, one must surely appeal to the same source to explain the properties of a hotter, more numerous and more energetic population of clouds.

In the previous section we identified the clouds under discussion with those in the tails of the velocity distribution observed by Blaauw (1952), and a similar distribution from the more recent observations of Siluk and Silk (1974). The latter authors proposed, in fact, that these clouds were inside supernova remnants and returned to the more numerous data of Adams (1949) to substantiate their suggestion. Considering only velocities > 20 km s^{-1}, the number of clouds having an absolute velocity greater than V was found to be proportional to $1/V^2$. According to Siluk and Silk (1974), this would be in reasonable agreement with the acceleration of clouds in the adiabatic phase of the expansion of remnants.

A direct comparison between our profile and their distribution is not possible because, as stated earlier, it is the atoms and not clouds that have been added together in the 21 cm profile. A distribution of masses with different temperatures (and hence optical depths) would further modify the distribution. Although distributions other than a Gaussian, like that of Siluk and Silk (1974), provide a reasonable fit over the higher velocity part of the profile, the available signal-to-noise ratio is not adequate to enable a meaningful distinction to be made. Finally, theoretical work in this complicated field is short of providing an unambiguous radial velocity distribution to be expected for clouds accelerated by one or more shocks.

The reasonable fit to a Gaussian, as seen in Fig. 1, makes possible however, a very simple computation of the total energy in these clouds, and provides the strongest argument we have for associating them with supernova remnants. As the thermal energies form a minor contribution for both the narrow and wide components in the profile, we could directly compare the energies associated with the 'peculiar' motions of the H I atoms themselves. The dispersion of the wide component ($\sigma_W \sim 35$ km s^{-1}) is 7 times greater than that of the narrow component ($\sigma_N \sim 5$ km s^{-1}), and it contains twice as much mass. The ratio of kinetic energies is therefore $(\sigma_W / \sigma_N)^2 \times (m_w / m_n) \approx 100$; the gas in the wide component has two orders of magnitude more energy than the cold clouds.

It would appear therefore that the motions of this population of clouds form the main reservoir of kinetic energy in interstellar neutral gas, as indicated in Paper I. If an input of supernova energy at a low efficiency is required to maintain even the motions of the cold clouds, we have no alternative but to ascribe the higher velocities of these hotter clouds to a more efficient utilisation of most of the energy in supernova shocks. Any theoretical model of the interstellar medium must, it appears to us, primarily account for their velocities, and for the difference from the velocity distribution of cold clouds.

If collisions between clouds are mainly responsible for dissipating the energies of their motions, then calculations such as by McKee and Ostriker (1977) (equations (58) to (61) of their paper), leading to a root mean square velocity of ~ 8 km s^{-1}, will have to be modified to explain the velocity spectrum of the hot clouds. The dissipation rate calculated on the basis of a *random* distribution of velocities of the order of 35 km s^{-1} leads to an embarrassingly high dissipation rate, much higher than the total input rate of energy from supernova explosions. On the other hand, if cloud-cloud collisions took very much longer, because clouds accelerated by the same shock tend to be moving in the same direction, then the dissipation rate would be reduced considerably.

That clouds probably do not move randomly, and hence rarely collide if ever, has also been concluded from observational studies of their motions by Heiles (1974), but in this case referring to colder material. In any event, we conclude that collisions between hot clouds must be relatively rare, and most likely less frequent than collisions with supernova shocks. As a consequence, many clouds may suffer several consecutive collisions with shocks, leading to faster, hotter and less massive clouds, to be found in the tail of the total distribution of velocities. Although the velocities of such clouds may be highly correlated in any particular region, a long line of sight will intersect many such domains and tend to produce a distribution with zero mean.

4. Discussion

4.1 *The Number of Hot Clouds*

We shall now discuss some of the implications of the conclusions reached in the preceding sections. We have seen that the total mass and the harmonic mean temperature of the gas in the hot clouds are approximately twice and four times the corresponding values in typical cold clouds. With these inputs, some constraints can be placed on the ratio of the number of clouds of each variety along a given line of sight. If the hot clouds are produced by the action of one or more shocks on cold clouds, we would expect their masses to be no higher than those of cold clouds, and very likely less, because of the evaporation which must accompany this process (McKee and Ostriker 1977).

Given the typical mass of such clouds, the radius will depend on the number density of atoms which will be about a fourth of that in cold clouds, if pressure equilibrium has established itself; the temperature in these clouds is four times that in cold clouds. The resulting ratio of the number of clouds per unit line of sight of each variety can be arrived at easily, and is given by

$$\nu_H / \nu_C = (\langle n_H \rangle / \langle n_C \rangle)\,(T_H / T_C)^{2/3}\,(M_C / M_H)^{1/3} = 5\,(M_C / M_H)^{1/3},$$

where ν is the number of clouds, $\langle n \rangle$ the average number density, T the temperature, M the mass, and the subscripts H and C refer to the hot and cold clouds respectively.

It varies from 5 to 1 for no change in mass but an increase in radius commensurate with pressure balance, and 6 to 1 for a decrease in mass to half that of cold clouds, and pressure balance. If there are 2·5 cold clouds per kpc, we could therefore expect a total of both varieties of 15 and 19 clouds per kpc respectively, for the two cases discussed above.

The number of clouds per kpc observed optically depends on the particular type and sensitivity of the observations. As mentioned earlier, Blaauw (1952) obtained 8 to 12 per kpc from the Ca II observations of Adams (1949). A recent photometric study by Knude (1979), in which special attention was paid to clouds producing only small reddening, yielded 6 to 8 clouds per kpc along a line of sight. Clouds not belonging to this special category would therefore contribute to substantially increasing this number.

High resolution interferometric observations by Hobbs (1974a) of the KI λ7699 line showed that there were 4·6 clouds per kpc (Hobbs 1974b). The choice of this particular line for the purpose of studying the properties of interstellar clouds was based on other considerations, and not for determining the frequency of occurrence of all types along the line of sight. That many clouds not producing a detectable KI $\lambda 7699$ line exist, is seen from observations by the same author (Hobbs 1974a), in which the number of stars toward which the D_2 and $\lambda 7699$ lines were observed were 77 and 17 respectively. This ratio suggests that the number of clouds per kpc producing D_2 lines could be as high as $77/17 \times 4{\cdot}6$ or ~ 21.

As the analysis by Blaauw (1952) was based on the early measurements of Adams (1949), of much lower sensitivity than the measurements of Hobbs (1974a), we feel that a reasonable estimate of the total number of clouds per kpc would be 15 to 20. Admittedly, our calculation of the number of clouds to be expected along a line of sight involved assumptions such as that clouds are spherical, which are certainly not borne out by observations. Our purpose was really to get a feeling for the increase in number, which we conclude is in good agreement with the other estimates, if the masses of, and number densities in hot clouds are typically less than those of the cold clouds.

Such a large number of hot clouds per kpc raises immediately the possibility of their being observable at intermediate and high galactic latitudes. We estimated a ratio of hot to cold clouds of $\approx 5:1$, and it was found from the Parkes survey (Radhakrishnan *et al.* 1972b) that cold clouds are typically separated along a line of sight by one full scale-thickness of the galactic disk. We would therefore expect to see 2 to 3 hot clouds per half-thickness of the galactic disk, assuming for the moment that conditions in the solar neighbourhood are no different from the average over a long line of sight in the galactic plane. Several such clouds should therefore be encountered along any line of sight at intermediate and even high galactic latitudes; the optical depths of such clouds should be typically below 0·1, and the spin temperatures in the hundreds of kelvins.

Dickey, Salpeter and Terzian (1978) have carried out a 21 cm absorption survey at high and intermediate galactic latitudes with the upgraded Arecibo telescope, and found a number of absorption features with optical depths in the range 0·1 to 0·01 and spin temperatures of a few hundred degrees. They have also surmised (Dickey, Salpeter and Terzian 1979), that a substantial part of the optically thin hydrogen they saw in emission, but whose optical depth was below their limits of detection, consists of low density, warm, intermediate velocity clouds. These results are in good qualitative agreement with what would be expected on the basis of our previous conclusions.

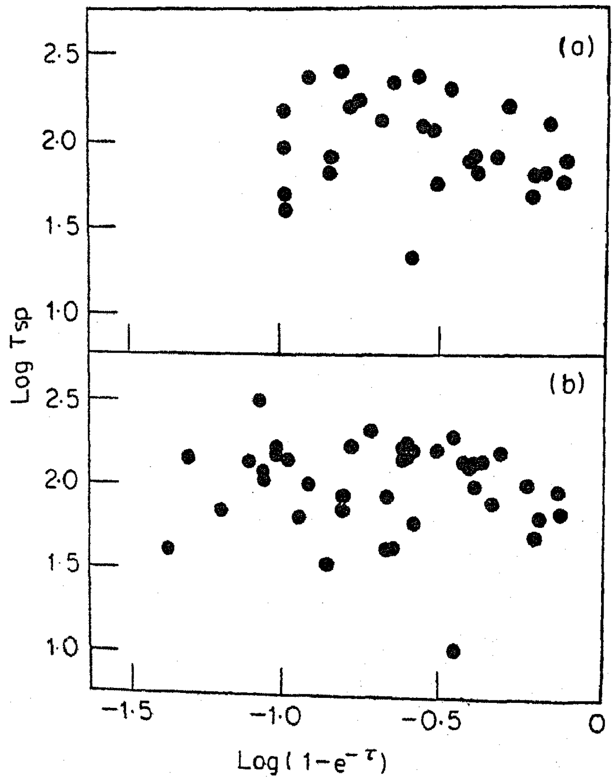
4.2 *Spin Temperatures*

We turn now to a discussion of spin temperatures. A connection between spin temperatures and optical depths, in that hotter clouds would tend to be optically thinner, is certainly to be expected on general grounds. The simple-minded relationship derived earlier on the assumption of pressure balance predicts that $\tau \propto M^{1/3} \times T^{-5/3}$. If there was a dependence of mass on temperature of the form $M \propto T^{\beta}$, this would modify the relationship between τ and T depending on the value of β. If $\beta = -1$, meaning that the masses of clouds are inversely proportional to their temperature, this would lead to $\tau \propto T^{-2}$. The relationship derived empirically by Dickey, Salpeter and Terzian (1978) from their sample, with values of $(1-e^{-\tau})$

spanning two orders of magnitude, reduces to this for small values of τ. While this might appear to be reasonably in agreement with what is expected, we have some reservations however.

The temperatures of ~ 30 clouds measured in the Parkes survey showed no discernible correlation with their optical depths which lie in the range $-1{\cdot}0 < \log\,(1-e^{-\tau}) < -0{\cdot}1$. A better sample of over 40 clouds having $-1{\cdot}4 < \log\,(1-e^{-\tau}) < -0{\cdot}1$ measured recently by Mebold *et al.* (1980) also shows no correlation of their spin temperatures with optical depth. These measurements are shown in Figs 6a and 6b. Thus, although a correlation of spin temperature with optical depth might be expected in any optical depth range, it appears that for clouds limited to the range $\log\,(1-e^{-\tau}) \geqslant -1{\cdot}0$, a significant empirical relationship of T_{spin} with τ is yet to be established.

If we assume that the principal reason for a difference in spin temperatures of interstellar clouds, is whether they belong to one or other of the two categories we have proposed, the measurements of Dickey, Salpeter and Terzian (1979) can be reconciled with those represented in Figs 6a and 6b. If this interpretation is correct, then the rms velocity for the higher temperature—and lower optical depth—features found by them should be greater than for the lower temperature ones. This is precisely what was found by Dickey, Salpeter and Terzian (1978) as discussed at the end of § 4 of their paper and shown in Fig. 45 of the same.



Figures 6a and b. The distribution of spin temperature versus optical depth for approximately 30 clouds measured in the Parkes survey (Radhakrishnan *et al.* 1972 b) a; and for ~ 40 clouds measured recently by Mebold *et al.* (1980) b. For clouds with optical depths in this range, no definite trend is apparent in either distribution.

A value of log $(1-e^{-\tau}) = -1{\cdot}0$ appears to be a reasonable dividing line below which hot, shocked clouds begin to make their appearance. The less sensitive surveys selected the cold clouds with higher optical depths, which apparently have little or no correlation with their spin temperatures. On the other hand, the Arecibo survey with its greater sensitivity, included several of the hot clouds; but a reliable empirical relationship between T and τ for the hot clouds alone may have to await the detection of larger numbers of this variety. In any case, the clear difference in rms velocities noted by Dickey, Salpeter and Terzian (1978), is further confirmation of our hypothesis of two distributions of clouds. The increased number of clouds per kpc found in the Arecibo survey, as compared to the Parkes value, is also in agreement with the picture we have outlined.

4.3 *Emission from Hot Clouds*

A serious quantitative disagreement exists however, between our picture and the amount of emission from optically thin hydrogen observed at intermediate and high latitudes. The average column density of optically thin material normalised to $|b| = 90°$, is $\sim 1{\cdot}4 \times 10^{20}$ cm^{-2} (Radhakrishnan *et al.* 1972b; Mebold 1972; Dickey, Salpeter and Terzian 1979). If the column density per unit path length of the hot clouds we see in the direction of the centre, were also to hold in the solar neighbourhood, there should be in *these clouds alone*, twice this observed value. If all the observed emission is attributed to them, this would imply that there is no intercloud gas at all, and we would still have accounted for only half the expected amount. Further, if they are separated clouds, as suggested by the optical evidence, they will not contribute to the pressure required to hold the cold clouds together, and which must therefore come only from hot coronal gas.

It seems to us that there is no compelling reason why the density of hot clouds in the solar neighbourhood should conform to the average obtained over a long line of sight. One would, in fact, expect fluctuations over a length scale comparable to the size of remnants at the stage when the shocks have become too weak to effectively accelerate clouds; also, over distances comparable to the separation between old remnants. The size of the solar neighbourhood observable at intermediate and high latitudes could well be of the order of the latter. If fluctuations can occur in the amount of hot-cloud material, as we find from its local deficiency, it is possible that the amount of intercloud material in any locality can also fluctuate over such distances. It is not inconceivable that there is an inverse correlation between the two, particularly if clouds of the two varieties are generated in different regions. We shall advance reasons for proposing such a separation in a later part of this section.

4.4 *Velocities of the Emitting gas*

We believe that a separation of the optically thin gas at intermediate and higher latitudes into an intercloud and hot cloud components may be possible by a careful analysis of emission profiles in different directions. Most of the optically thin gas observed in the Parkes survey, and attributed entirely to an intercloud medium, has an internal dispersion of approximately 11 km s^{-1}; its mean velocity is separated from the velocity of absorbing clouds in the same direction by a typically smaller value, as is immediately evident from an inspection of the spectra (example page 43 of the Parkes survey). Such a correlation in velocities has also been noted in the more recent Arecibo data by Dickey, Salpeter and Terzian (1979), and has been interpreted by them as evidence against an ' extreme two-phase ' model. Any two-phase model against which such a correlation can be construed as evidence, will indeed have to be extreme, in that it must require total independence in velocity space of the two phases. As far as we know, no theoretical model or observational study of the intercloud gas has required or claimed such independence.

The simplest considerations lead one in fact to expect a correlation of velocities. Whether the intercloud gas has been left over from cloud condensation, or created from evaporation of clouds, some sharing of the motions would be natural. Even if a cloud were injected into a motionless medium, some of its motion should gradually be imparted to the immediately surrounding intercloud gas. If a cloud were to move through a rarified—but hotter—medium with a velocity comparable to the thermal velocities in the medium, the pressure balance will be upset and a shock would be set up. In addition to slowing down the cloud through drag, it is likely to disrupt it. According to Chevalier (1977) and references there in (Gurzadyan 1970; Richtmyer 1960; Woodward 1976), the boundary between high and low density regions is unstable after being shocked and the deceleration of a dense gas by a low density gas leads to its breakup as it is penetrated by the low density gas. If clouds co-exist with a medium, and have velocities comparable to the thermal velocities in the medium, one must therefore expect to find much smaller differential velocities, or in other words a correlation of the velocities.

Returning now to the optically thin gas seen in emission in the solar neighbourhood, we said earlier that it could have contributions both from hot clouds and true intercloud gas. We have established that the hot clouds occupy a very much larger volume in velocity space than the cold clouds. If they are concentrations of gas like the cold clouds, but different only in their temperature and their velocities, their motions will be independent in velocity space. If all the gas seen in emission were due to hot clouds, it would be most reasonable to expect near-total decorrelation of the velocities. As pointed out above, the observations show that there is considerable correlation. We interpret this as strong evidence that a considerable fraction of the emitting gas is intercloud material (see also recent discussion by Heiles 1980).

In profiles representing only optically thin material, we expect the hot cloud contributions to have a wider dispersion (~ 35 km s^{-1}) than the intercloud medium (~ 10 km s^{-1}). The combined contributions, when not clearly separable, would mimic an exponential, as discussed earlier in the case of the two cloud populations. Evidence of this may be seen in Fig. 3 of Dickey, Salpeter and Terzian (1979), where they show the normalised emission averaged over different source directions at intermediate and high galactic latitudes.

4.5 *Where are the Clouds Found ?*

If we are right in thinking that cloud velocities will tend to be lower than the sonic speed in a surrounding medium, we are then forced to the interesting conclusion that the hot clouds with speeds of the order of 60 km s^{-1} cannot last in a neutral intercloud medium where the temperatures are believed to be typically 8000 K. On the other hand, if they were immersed in coronal gas with temperatures approaching a million degrees, the problem does not arise. In a recent study, McKee, Cowie and Ostriker (1978) discuss the production of fast clouds of neutral hydrogen with column densities $\sim 10^{19}$ cm^{-2} accelerated by the ram pressure of the expanding interior shocked gas. These clouds will of course be moving in the hot coronal gas inside the remnant.

The evidence presented in this paper for two distinct cloud populations seems to point strongly to a picture in which the fast and slow clouds are immersed respectively in hot coronal gas and a warm intercloud medium in separated regions in the galactic disk. Such a separation would facilitate the explanation of many observed facts beginning with the deficiency of hot clouds in the solar neighbourhood. These clouds would clearly acquire their velocities from the supernova shocks which overtook them, and within which they will be found. On the other hand, if the low velocities of the cold clouds were typical of the velocities of gas in the regions where they are formed, we would have a natural explanation of their motions. Cloud-cloud collisions dissipating part of the energy available before the collision, need not be invoked to produce a 'thermalised' distribution with $\sigma \sim 5$ km s^{-1}.

The mean velocity of the gas caught and compressed between the shock fronts of adjacent remnants in their late stages will be roughly half the difference in the velocities of these shocks, when the sum of their radii equals the distance between the explosion sites. A simple-minded calculation assuming a 30 year period for the occurrence rate of supernovae in the Galaxy leads to the relation $\Delta T_6 \approx 2 \times 10^3 D_{\mathrm{pc}}^{-2}$, where ΔT_6 is the time difference in millions of years between supernova explosions separated by a distance D in pc, calculated on the basis of a 50 per cent probability. It has been assumed that the effective area of the galactic disk in which supernovae occur is that of a circle of radius 10 kpc. Thus, to within a factor of 2 or so, there is a 50 per cent chance that remnants differing in age by less than a million years, will be separated in distance by less than ~ 50 pc. A proper calculation of the mean velocity of gas in the meeting area of the two shocks will involve the appropriate equations from a theory for the development of remnants in their late stages. But a rough estimate seems to suggest that the velocities will be of the order of the velocities of cold clouds. We therefore propose that the regions between old and neighbouring supernova remnants provide the conditions and occupy enough volume to account for the formation of the cold clouds.

This picture is not too different from that proposed by McKee and Ostriker (1977) for the formation of cold clouds. According to them, condensation of cold matter will typically occur only on the clouds passed by shocks during the late stages of supernova remnant expansion. A slight modification of this picture is one in which clouds caught between two old SNRs will act as nucleii for the condensation of the swept up material leaving cold dense clouds with a low velocity. The gas which has not condensed onto the clouds will remain as a neutral intercloud medium. Conditions in such regions may be very similar to those considered by Field, Goldsmith and Habing (1969), with the only difference that cosmic rays play no part in heating the gas. If so, cold clouds will spontaneously condense out of the medium; further they will show the poor T_{spin} versus τ correlation illustrated well in Fig. 6b, because they are attempting to reach an equilibrium temperature. Such clouds, in course of time, when passed by subsequent but rapid shocks will suffer heating, partial evaporation of their masses, and acceleration to many times their velocities thus moving them into the population of hot, shocked clouds we identify with the wide feature of our absorption spectrum.

Finally we note that there does exist independent observational evidence in support of a picture in which dense cold neutral hydrogen is always found in shells. From a detailed study of Per OB2 and Sco OB2, Sancisi (1974) proposed that the birth places of these stellar associations were shells of neutral hydrogen surrounding old and strongly decelerated supernova remnants. From a very extensive survey of the 21 cm emission over a large part of the sky, Heiles (1976) concluded that the number of shells is large, and that nearly every H I density concentration appears to be part of a large arc and therefore a shell. He has also made the point that the existence of shells or sheets of interstellar gas has previously been deduced by many different techniques.

5. Conclusions

The main contribution of the present work is the identification of a component of the interstellar gas which should assume the central role in any picture describing its energetics. We started with the new wide feature detected in the Gaussian analysis of the 21 cm absorption spectrum of Sgr A (Paper I). The spin temperature of the gas was derived by a comparison with observations on the Bonn 100 metre telescope by Sanders, Wrixon and Mebold (1977), and found to be 300 K±50. We showed that the gas represented by this feature must be globally distributed in the galaxy, by arguments involving its near-zero mean velocity, its column density, and by a comparison with velocity distributions obtained by optical and radio observations in many other directions in the Galaxy. The exponential form attributed to these other velocity distributions was shown to be a consequence of the superposition of two distributions, one narrow and one wide, the latter of which was incompletely sampled.

The column density of the wide feature was shown to indicate that in the hot clouds it represented, there was twice as much total hydrogen as found in cold clouds. We then argued that an association of these hot clouds with supernova shocks was inevitable. We based this argument on the correlation of cloud temperatures with velocity, the sodium I to calcium II anomaly observed in high velocity optical clouds and attributed to the effects of shocks on grains (Spitzer 1978), and most importantly on the high kinetic energy contained in these clouds, $\sim$ 100 times that in cold clouds.

If most of the mass in interstellar clouds was moving with an rms velocity of 35 km s^{-1}, some constraints can be placed on the randomness of these velocities. Cloud-cloud collisions at such velocities would lead to an excessively high dissipation rate of energy if the motions were random, but the velocities are more likely to be correlated because of acceleration by large shock fronts. It was concluded that collisions of clouds with supernova shocks would be more likely than with other clouds.

The number of hot clouds estimated from the total column density, the temperature, and some assumptions of the masses, was predicted to be 15–20 clouds per kpc along a line of sight, in rough agreement with a number estimated from the optical measurements of Hobbs (1974a, b). The observations of Dickey, Salpeter and Terzian (1978) of clouds with low optical depth, high spin temperature, and a high velocity were shown to be in agreement with our picture. We proposed however, that the relationship of spin temperature with optical depth may be different in different optical depth ranges, as suggested by a comparison with the measurements of Mebold *et al.* (1980).

We found that the solar neighbourhood is deficient in the emission expected from hot clouds alone by at least 50 per cent. Fluctuations in the composition of interstellar gas occur therefore over volumes of the order of that of the solar neighbourhood, as would be expected in a supernova dominated picture of the interstellar medium.

The velocity correlation between the optically thin gas seen only in HI emission, and the optically thick gas seen in absorption, was interpreted as evidence that a substantial fraction of the optically thin gas in the solar neighbourhood must be intercloud material. If all of it was due to hot clouds alone, the motions would be independent and no velocity correlation would have been observed with the motions of the cold clouds. It was suggested that a careful analysis of the emission from optically thin hydrogen might enable a separation into true intercloud and hot cloud components. The hot cloud emission should show a much wider dispersion than the intercloud emission and hence permit a separation. Some evidence for this was already present in the measurements of Dickey, Salpeter and Terzian (1978).

It was argued that hot clouds are not likely to be found in regions with intercloud gas, as their velocities in this medium would be highly supersonic. In the interior of remnants, the high temperature of the coronal gas would make such velocities subsonic. It was proposed therefore that the two varieties of clouds would be generally found in separated regions; the interior of remnants would contain hot clouds heated and accelerated by the shocks which overtook them, and cold clouds would be found in the regions in-between remnants where intercloud gas will also exist. The cold clouds probably condense out of the intercloud gas between supernova remnants due to instabilities such as discussed by Field, Goldsmith and Habing (1969). If clouds formed in this manner, they would tend to acquire an equilibrium temperature, and hence show a poor correlation with optical depth as indicated by the observations.

The low velocities of cold clouds were attributed to the velocities of the gas from which they condense, and it was argued that such gas caught between neighbouring remnants in their late stages would have rms velocities of ~ 5 km s^{-1}. The presence of a substantial amount of intercloud gas, and the deficiency of hot clouds in the solar neighbourhood was attributed to its location in-between old supernova remnants, rather than within one.

To sum up, an analysis of the 21 cm absorption spectrum of a strong continuum source well placed in the galaxy has led to a model in which the volume of the galactic disk contains, in addition to the hot bubbles representing supernova remnants (Cox and Smith 1974), cooler in-between regions. Clouds with $N_H \leqslant 10^{20}$ cm^{-1}, N_H/kpc $\sim 2 \times 10^{21}$ cm^{-2} kpc^{-1}, $T_s \sim 300$ K, and speeds of ~ 60 km s^{-1} are found inside bubbles. Outside of them, we have regions filled with an intercloud medium imbedded in which are cold dense clouds with $N_H \sim 4 \times 10^{20}$ cm^{-2}, N_H/kpc $\sim 10^{21}$ cm^{-2} kpc^{-1}, T_s typically between 50 and 100 K, and speeds ~ 8 km s^{-1}.

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Appendix

The spin temperature of the wide component

We shall estimate the spin temperature of the gas in the wide component by combining the Parkes interferometer optical depth measurements with the antenna temperatures obtained by Sanders, Wrixon and Mebold (1977) with the Bonn 100 metre telescope. These measurements are shown in Figs 2a and 2b. We see in 2a the total optical depth profile obtained in the direction of Sgr A from Paper I, and superimposed on it (dashed line) the Gaussian fitted to the wide component (Fig. 1d of this paper). It will be seen that in the narrow velocity ranges centred at approximately -38 km s^{-1}, -18 km s^{-1} and $+26$ km s^{-1}, the contribution to the total optical depth is, to within the errors of the measurement, only from the wide component. The optical depths at these velocities are indicated in Fig. 2a and the Bonn antenna temperatures at the same velocities are indicated in Fig. 2b. The optical depths are reasonably low at all 3 velocities, and the harmonic mean spin temperatures can be derived from the single dish antenna temperatures which contain both emission and absorption contributions. At any given velocity,

$$T_A = -T_c(1-e^{-\tau}) + \eta\, T_s(1-e^{-\alpha\tau}),$$

$$\text{or } T_s = \frac{T_A + T_c(1-e^{-\tau})}{\eta\,(1-e^{-\alpha\tau})},$$

where T_A is the Bonn antenna temperature from Fig. 2b,

$T_c = 600$ K ± 50 the continuum antenna temperature on Sgr A (provided by Mebold),
η is the beam efficiency 70 ± 3 per cent (Mebold and Hills 1975),
τ taken from Fig. 2a,
α taken to be 2·35 ± 0·35 (see below).

The emission contribution will come both from the path length to the galactic centre, and also from beyond the galactic centre all along the direction $l = 0$, $b = 0$. The factor α is the ratio of the emission to absorption path lengths involved. As the uncertainty in this quantity is large, we have taken α to vary from 2 to 2·7 in estimating our total errors. We have assumed here that the emission contribution from behind the galactic centre is not diminished in any way by the continuum source —a very reasonable assumption considering the relative sizes of source and antenna beam, and the optical thinness of most continuum sources at this frequency. The spin temperatures derived on this basis are 290 ± 35, 400 ± 40, and 350 ± 40 at the three velocities.

There appears to be a correlation of the derived spin temperatures at the three velocities with the optical depths or $|V|$; as the absorption profile is centred at zero, these latter quantities vary together. No significant correlation with optical depth is to be expected over the central portion of the wide feature, as there will be a mixture of clouds of all speeds, of which we are measuring only one component of the motion. Some correlation with velocity is to be expected however, due to a contribution to the antenna temperature from the wings of the emission profile from true intercloud gas along the line of sight. While the intercloud emission should be negligible at -38 km s^{-1}, there would be some contribution at smaller velocities.

A recalculation of the temperatures was therefore carried out, allowing for intercloud emission including its partial absorption by hot clouds. Based on measurements obtained in the Parkes survey, the dispersion of intercloud gas was taken to be 11 km s^{-1} in a direction free of galactic rotation effects, and its total column density to the far end of the Galaxy was taken to be $N_{\mathrm{ICM}} \approx 1{\cdot}4 \times 10^{22}$ cm^{-2}. The new values of temperature obtained were 290 K, 230 K and 300 K, respectively for the three velocities given earlier.

These new values would represent a gross overcorrection if there were no intercloud gas at all in the Galaxy. As discussed in § 4 we believe there is, but perhaps somewhat less than we have assumed here. We conclude that 300 K ± 50 is therefore a very reasonable estimate of the harmonic mean temperature of the gas in the wide feature.

References

Adams, W. S. 1949, *Astrophys. J.*, **109**, 354.

Blaauw, A. 1952, *Bull. astr. Inst. Netherl.*, **11**, 459.

Chevalier, R. A. 1977, *A. Rev. Astr. Astrophys.*, **15**, 175.

Clark, B. G. 1965, *Astrophys. J.*, **142**, 1398.

Cox, D. P., Smith, B. W. 1974, *Astrophys. J.*, **189**, L105.

Dickey, J. M., Salpeter, E. E., Terzian, Y. 1978, *Astrophys. J. Suppl. Ser.*, **36**, 77.

Dickey, J. M., Salpeter, E. E., Terzian, Y. 1979, *Astrophys. J.*, **228**, 465.

Field, G. B., Goldsmith, D. W., Habing, H. J. 1969, *Astrophys. J.*, **155**, L149.

Gurzadyan, G. A. 1970, *Planetary Nebulae*, D. Reidel, Dordrecht.

Heiles, C. 1974, in *Galactic Radio Astronomy*, Eds F. J. Kerr and Simonson III, D. Reidel, Dordrecht, p. 13.

Heiles, C. 1976, *Astrophys. J.*, **208**, L137.

Heiles, C. 1980, *Astrophys. J.*, **235**, 833.

Hobbs, L. M. 1974a, *Astrophys. J.*, **191**, 381.

Hobbs, L. M. 1974b, *Astrophys. J.*, **191**, 395.

Jenkins, E. B., Meloy, D. A. 1974, *Astrophys. J.*, **193**, L121.

Knude, J. 1979, *Astr. Astrophys.*, **71**, 344.

Mast, J. W., Goldstein, S. J. Jr. 1970, *Astrophys. J.*, **159**, 319.

McKee, C. F., Ostriker, J. P. 1977, *Astrophys. J.*, **218**, 148.

McKee, C. F., Cowie, L. L., Ostriker, J. P. 1978, *Astrophys. J.*, **219**, L23.

Mebold, U. 1972, *Astr. Astrophys.*, **19**, 13.

Mebold, U., Hills, D. L. 1975, *Astr. Astrophys.*, **42**, 187.

Mebold, U., Winnberg, A., Goss, W. M., Kalberla, P. M. W. 1980, preprint.

Radhakrishnan, V., Goss, W. M. 1972, *Astrophys. J. Suppl. Ser.*, **24**, 161.

Radhakrishnan, V., Goss, W. M., Murray, J. D., Brooks, J. W. 1972a, *Astrophys. J. Suppl. Ser.*, **24**, 49.

Radhakrishnan, V., Murray, J. D., Lockhart, P., Whittle, R. P. J. 1972b, *Astrophys. J. Suppl. Ser.*, **24**, 15.

Radhakrishnan, V., Sarma N. V. G. 1980, *Astr. Astrophys.*, **85**, 249.

Richtmyer, R. D. 1960, *Commun. Pure Appl. Math.*, **13**, 297.

Routly, P. M., Spitzer, L. Jr. 1952, *Astrophys. J.*, **115**, 227.

Sancisi, R. 1974, in *Galactic Radio Astronomy*, Eds F. J. Kerr and Simonson III, D. Reidel, Dordrecht, p. 115.

Sanders, R. H., Wrixon, G. T., Mebold, U. 1977, *Astr. Astrophys.*, **61**, 329.

Siluk, R. S., Silk, J. 1974, *Astrophys. J.*, **192**, 51.

Spitzer, L. Jr. 1956, *Astrophys. J.*, **124**, 20.

Spitzer, L. Jr. 1968, *Diffuse Matter in Space*, Wiley Interscience, New York.

Spitzer, L. Jr. 1978, *Physical Processes in the Interstellar Medium*, Wiley-Interscience, New York.

Spitzer, L. Jr., Jenkins, E. B. 1975, *A. Rev. Astr. Astrophys.*, **13**, 133.

Williamson, F. O., Sanders, W. T., Kraushaar, W. L., McCammon, D., Borken, R., Bunner, A. N. 1974, *Astrophys. J.*, **193**, L133.

Woodward, P. R. 1976, *Astrophys. J.*, **207**, 484.

York, D. G. 1974, *Astrophys. J.*, **193**, L127.