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NEUTRAL HYDROGEN CLOUD DISTANCES AND THE STRENGTH OF THE INTERSTELLAR MAGNETIC FIELD

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ABSTRACT. If HI clouds exist in pressure equilibrium in an environment where gas pressure is a function of z-distance and if HI cloud density is a function of z-distance, it can be shown that a quantity called the Virial Measure is a function of z-distance. The Virial Measure is that distance at which a cloud would be in gravitational equilibrium if its internal kinetic temperature is indicated by profile linewidth. The Virial Measure is derived from observed cloud parameters and has been calibrated for clouds of known distance so that it can be used to determine the distance to other HI clouds. The magnitude of various terms in the virial equation can thus be derived for several hundred HI clouds. It is demonstrated that the strength of the interstellar magnetic field is a function of z-distance.

1. THE DISTANCE TO HI CLOUDS

The distance at which an HI cloud would be in gravitational equilibrium is very much greater than its real distance. This distance, to be called the Virial Measure, D_v, has very different values for different populations of HI clouds. Sufficient data exist for clouds of known distance—either local clouds or others whose distances can be determined kinematically—to allow D_v to be calibrated with respect to z-distance.

The Virial Measure is found by equating the gravitational energy term, W, with $2\mathcal{T}$ the thermal energy term, in the virial equation. Neglecting other terms

$$W = 2\mathcal{T}$$

or

$$\frac{3GM^2}{5R} = 3NkT_k. \qquad (1)$$

R = cloud radius, T_k =cloud kinetic temperature, G and k the usual constants, M the cloud mass, and N the total number of atoms in the cloud. It is assumed that the cloud contains only HI and that observed HI profile linewidths are indicative of cloud kinetic temperatures, T_k.

The published data on several hundred HI clouds give values for cloud mass (Mr^{-2}) in solar masses at the unknown distance (r, in kpc), the linewidth at half peak intensity (ΔV, in km/s) and angular diameter (θ, in degrees) at half peak intensity.

It can be shown (Verschuur, 1986a) that if D_V is the distance at which Equation 1 is satisfied, then

$$D_V = \frac{1.55\,(\Delta V)^2\,\theta}{(Mr^{-2})} \quad \text{Mpc.} \qquad (2)$$

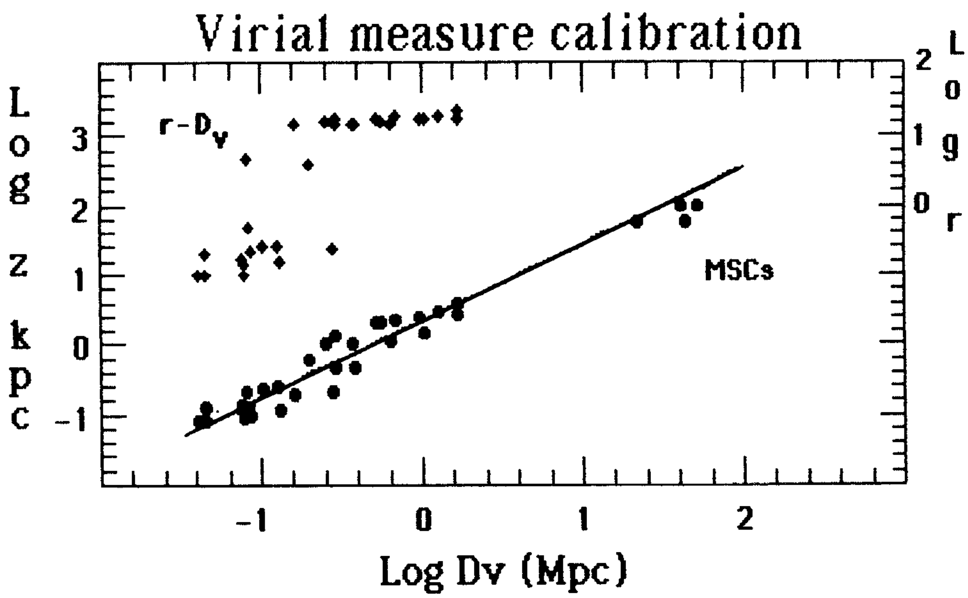

Figure 1. The calibration of the Virial Measure in terms of z-distance. Filled circles represent clouds, or averages for groups of up to 120 clouds, whose distances have been estimated by the original authors or were kinematically derived in the present work. Small plus signs indicate distance from the sun with the axis shifted 2 units. The Magellanic Stream Clouds are represented by four points at the right, but these were not used to determine the best-fit line.

Figure 1 shows the value of D_V plotted as a function of z-distance. Details of the calibration are given by Verschuur (1986a). A flat rotation law and the newly agreed-upon solar location and motion (8.5 kpc, 220 km/s) were used to establish kinematic distances and these clouds are all at or beyond the solar circle.

The best-fit line drawn in Figure 1, derived without using the Magellanic Streams clouds at the upper right of the line, is defined by

$$\log z = 1.10 \log D_V - 2.95 \quad (3)$$

where z and D_V are in kpc. Thus it appears that if D_V can be derived for a cloud, the cloud's distance can be found from Equation 3.

In order to highlight the fact that D_V is a function of z-distance and not of distance from the sun, the Virial Measure values are also plotted with respect to r. These are shifted vertically by two decades in Figure 1. No direct relationship between D_V and r exists.

Something other than gravitational attraction is clearly acting to produce the relation shown in Figure 1. It is hypothesized that intercloud gas pressure, which may be a function of z in the halo, determines HI cloud stability. For the clouds of known distance, and for other HI clouds whose distances can now be derived using the relationship given in Equation 3, it is possible to find values of the internal gas pressure, nT, as a function of z-distance. This was done by first deriving the value for a quantity nTr directly from published cloud data. From Verschuur (1986a),

$$nTr = 0.32 \frac{\Delta V}{\theta} (Mr^{-2}) \quad cm^{-3}\, K\, kpc. \quad (4)$$

Once a cloud's distance is known a value for nT can be derived. In Figure 2 this quantity is plotted for all clouds in the data base. The best-fit line for the emission clouds in Figure 2 is found to be

$$\log nT = 3.62 - 0.72 \log z \quad (5)$$

with nT in cm^{-3} K and z in kpc. Similar data for the Verschuur cold clouds, the Heiles cloudlets, and absorption clouds whose densities and diameters have been measured by independent means, are plotted as plus signs in Figure 2 and produce

$$\log nT = 2.45 - 0.78 \log z. \qquad (6)$$

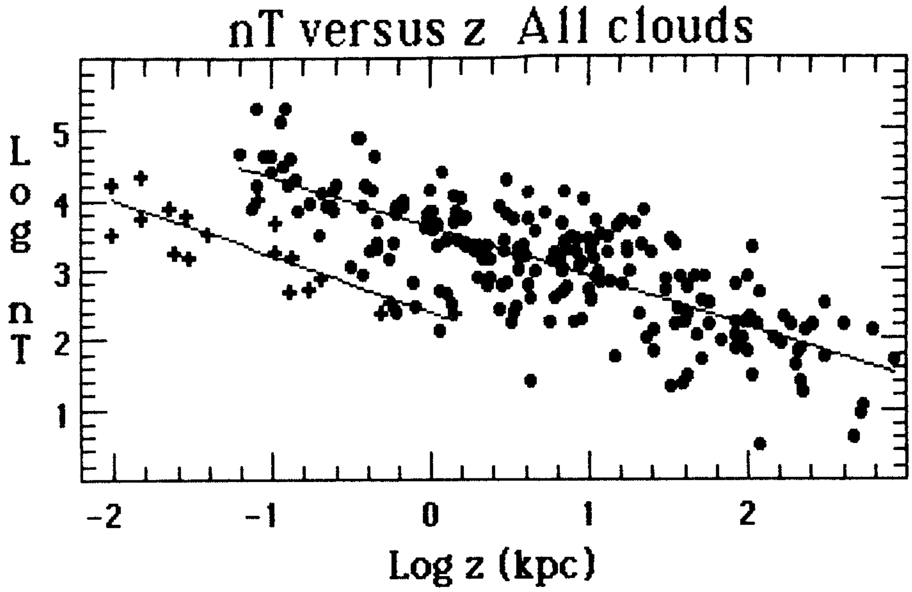

Figure 2. The gas pressure term, nT, as a function of distance from the galactic disk for clouds observed in emission (filled circles) and absorption (plus signs). The distances to the calibrators are independently known while the distance to all the clouds were found from Equation 3. The Verschuur cold clouds and a point representing the Heiles cloudlets have been included with this group. The best-fit lines to these two sets of data show clear and distinct differences as well as a common z-dependence.

Several important points emerge from a study of Figure 2:

1. The gas pressure in the emission features is clearly a function of z-distance.

2. If HI clouds exist in pressure equilibrium then we cannot have a condition where one group of clouds, those seen in emission, exist in a higher pressure regime than do the colder, absorption, clouds at the same z-distances. Examination of the initial assumptions reveals that emission profile linewidth is probably not a measure of cloud kinetic temperature. Some other cause for line broadening must be found, and whatever the reason it will have to account for the relationship found in Figure 1.

3. Several clouds are located at very great distances from the disk, more than 100 kpc away. However, the analysis implicitly assumes that nT is stratified parallel to the galactic disk. This assumption needs to be modified because at greater distances halo gas pressure—which must

utimately changes smoothly into to an intergalactic gas pressure—is more likely to be dependent on distance from the galactic center. The 'halo' gas pressure term is likely to drop to some ambient intergalactic value at distances of the order of several hundred kpc and the absolute value of derived distances beyond this are likely to be in error. The available data do indicate that the so-called very-high-velocity clouds and the Magellanic Stream clouds lie in intergalactic space.

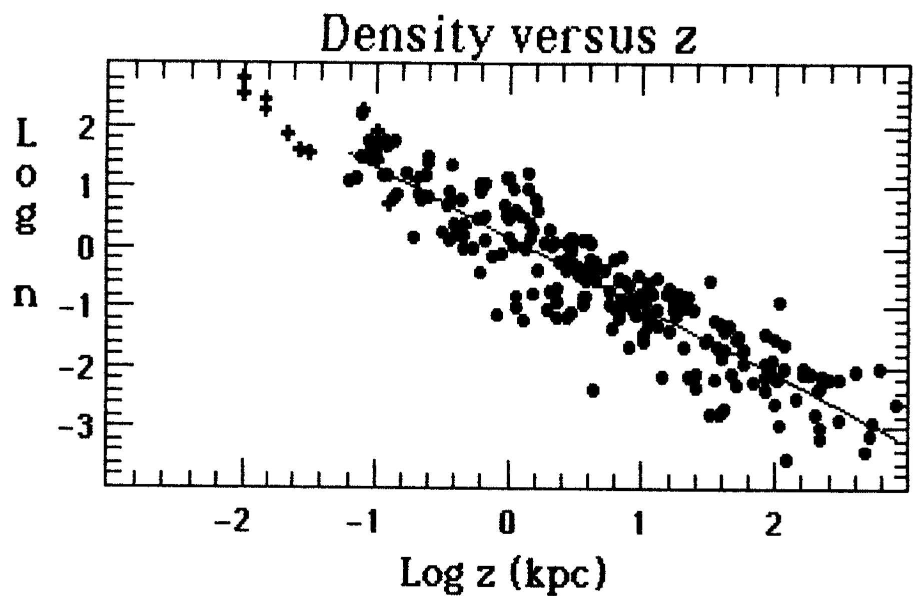

Figure 3. HI cloud density as a function of distance from the galactic disk. Filled circles refer to the emission clouds while the plus signs refer to the cold cloud and absorption line data. The line was fitted only to the emission clouds yet the absorption cloud information, determined in a completely independent manner, fits this line very well.

Next, the values for cloud densities can be determined from the data. This was done by taking the nT values and dividing by a temperature given by the linewidth, originally assumed to indicate T_k. Figure 3 plots the value of HI cloud density versus z-distance and shows that this is also z-dependent. The best-fit line is given by

$$\log n = 0.18 - 1.14 \log z. \quad (7)$$

The absorption line and cold cloud data are plotted as small plus signs and lie on an extension of the line fit to the emission cloud data or disappear into the jumble of these data. The densities for these two sets of clouds were determined by independent methods.

2. WHY VIRIAL MEASURE IS A FUNCTION OF Z-DISTANCE

It can be shown that if both the nT and n values are functions of z, then D_V must be a function of z as well.

Consider Equations 5 and 6 in the form

$$nT = A\, z^{\alpha} \tag{8}$$

and

$$n = B\, z^{\beta}. \tag{9}$$

If we ignore constant terms, we can consider the parameters applicable to a cloud of diameter θ at a height z kpc. Its mass, M, will be given by n R^3 where R is the cloud radius given by

$$R = \frac{\theta\, r}{2}.$$

Therefore, using Equation 9, we can write

$$M = B\, z^{\beta}\, \theta^3\, r^3. \tag{10}$$

The left hand side of Equation 1 can then be written as

$$W = (B\, z^{\beta})^2\, \theta^5\, r^5, \tag{11}$$

ignoring other constant terms.

For the right-hand side of Equation 1, we can write

$$2\mathcal{T} = N\, k\, T_k = n\, T\, R^3$$

Using Equation 8, we obtain

$$2\mathcal{T} = A\, z^{\alpha}\, \theta^3\, r^3. \tag{12}$$

D_V, was originally defined by setting Equations 11 and 12 equal. Thus, solving for D_V, and evaluating the constants, we find that

$$D_V = \frac{1.13}{\theta} \sqrt{\frac{A}{B^2}} \times z^{\frac{(\alpha - 2\beta)}{2}} . \tag{13}$$

From Figures 2 and 3 we derived Equations 5 and 7 and thus have values for A, B, α, and β. Equation 13 then becomes

$$D_V = \frac{47.46}{\theta} \times z^{0.785} . \tag{14}$$

The Virial Measure is found to be a function of angular diameter as well as z-distance, in which case we may ask why such a dramatic relationship between D_V and z, as was revealed in Figure 1, became manifested? It turns out that the majority of the clouds have diameters in the range $0.4 < \theta < 1.2°$ with the median value of θ for the calibrators of 1°. Thus, to first order, we can assume that θ is a constant and, setting $\theta = 1$, Equation 14 becomes

$$\log z = 1.27 \log D_V - 2.14. \tag{15}$$

Equation 15 has the same form as Equation 3—which was based on observations. The exponent is the same, within observational uncertainty, but the constant term is a little different. Uncertainties in the assumptions of a plane-parallel layered galaxy, cloud definition (assumption of cloud symmetry), observational scatter, and so on, may be acting to make the agreement less than perfect.

It appears that the D_V-z relation is the consequence of the hydrogen clouds being in pressure equilibrium in a medium in which nT and cloud HI density are both functions of z. The Virial Measure may be used to determine the distance to other HI clouds, provided they have approximately the same angular diameter as the calibrators.

3. CLOUD PROPERTIES AND THE STRENGTH OF THE INTERSTELLAR FIELD

During an early phase of this research an interesting 'coincidence' was noticed in connection to the gas pressure term, nT. If one could account for line broadening in terms of an Alfvén velocity spread, the strength of the interstellar magnetic field could be simply related to nT. This idea had a short half-life but caused the author to look at the published 21-cm Zeeman effect data in order to determine whether the magnetic field in HI clouds might be a function of z-distance. Figure 4 shows the results of this work, summarized by Verschuur (1986b).

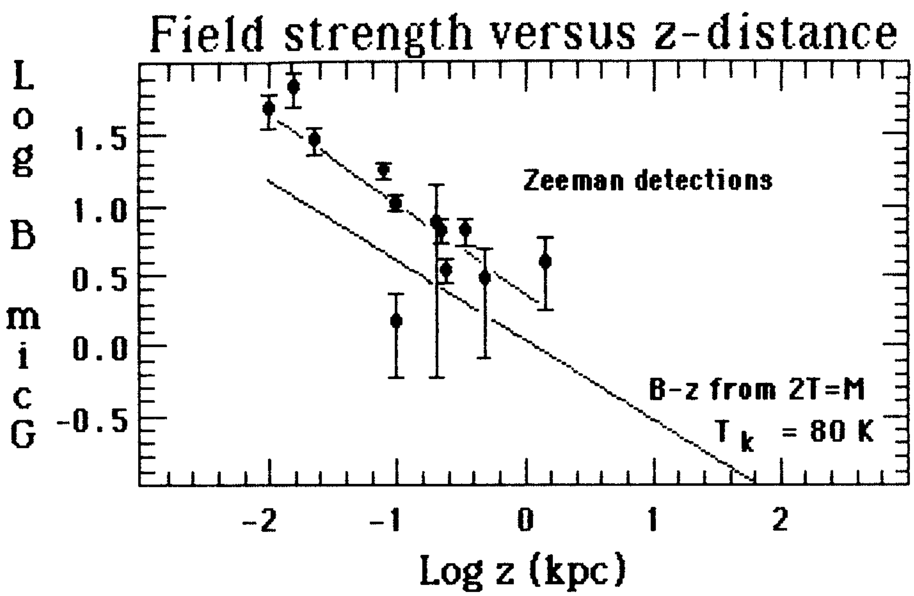

Figure 5. The strength of the interstellar magnetic field based on Zeeman effect measurements in HI clouds as a function of z-distance of the clouds. Error bars indicate two standard deviations. The upper line is the best-fit to the Zeeman data. The lower line is a field derived from equating the thermal energy content with magnetic energy in emission clouds believed to be in pressure equilibrium with their environment. Cloud kinetic temperature is assumed to be 80 K.

The important point that emerges from Figure 5 is that the interstellar magnetic field strength may, indeed, also be a function of z-distance. At z<100 pc it appears that the B > 10 μGauss, enough to align interstellar dust grains (Aanestad and Purcell, 1973).

The line fitted to the field detections, all line-of-sight components, is given by:

$$\log B = 0.38 - 0.64 \log z \qquad (16)$$

with B in μGauss and z in kpc.

An independent means for finding the value of the interstellar magnetic field is suggested by the distance analysis discussed in this paper. Once an HI cloud's distance is known we are able to derive all its properties, provided its kinetic temperature is known. Based on an examination of the n-z plot in Figure 3, and recognizing that the absorption cloud kinetic temperatures are well-known, and around 80 K, it is seen that the 'true' value for the cloud pressure may be found by adopting a value for the cloud kinetic temperature of about 80 K. Thus the values of the cloud gravitational energy content, W, the thermal content, 2 $\mathcal{T}$(Equation 1), and the magnetic energy content, **M** ($=B^2/8\pi \times$ Volume), can be derived, where B is assumed to be given by Equation 16.

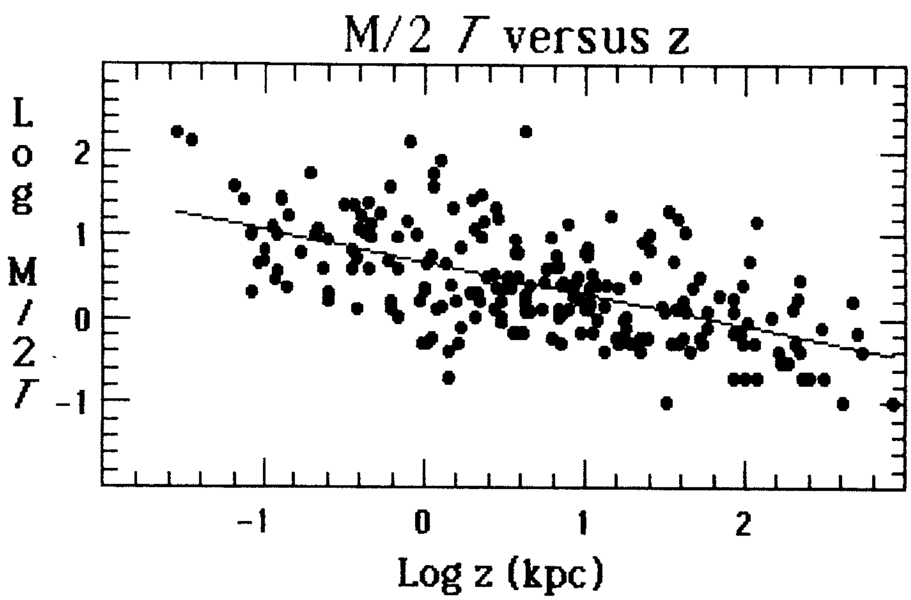

Figure 5. The ratio of magnetic energy content, M, to thermal energy content, 2 $\mathcal{T}$ for all the emisson clouds in the data-base plotted as function of z-distance. The field strength, B, was derived from Equation 16 and the value of T_k was taken to be 80 K in all clouds.

The values of W, 2 $\mathcal{T}$ and **M** were derived for several hundred clouds in the data base and Figure 5 shows the ratio of **M**/2 $\mathcal{T}$ as a function of z-distance. This ratio is z-dependence and given by

$$\log (\mathbf{M}/2\mathcal{T}) = 0.68 - 0.38 \log z. \qquad (16)$$

Figure 5 implies that at low z-distances either the field dominates the gas pressure—contrary to our original assumptions and interpretation of the data (above)—or the strength of the adopted field (based on the Zeeman data) is too large. Thus this approach was reversed. Under the assumption that the clouds are in pressure equilibrium and fields are frozen-in one may find the value of the field strength that would cause the two energy terms, $2\mathcal{T}$ and $\mathbf{M}$, to balance. Using Equation 16, the mean interstellar magnetic field strength is given by:

$$\log B = 0.05 - 0.57 \log z. \qquad (18)$$

The form of Equation 18 was sketched in Figure 4 as the lower line. The exponent is nearly the same as indicated by the Zeeman effect data—Equation 16. The field strength derived from equating magnetic and thermal energy densities would be more directly equal to that found from the Zeeman effect data if $T_k = 300$ K. However, the clouds in which the Zeeman measurements indicate the strongest fields are also found to have a gravitational energy content of the same order as the thermal content, suggesting that these clouds might be near to gravitational equilibrium. The fields in these clouds may be 'amplified' by gravitational contraction of these clouds, but if this is true the amplification must be considered with respect to ambient densities and fields indicated by the n-z and B-z plots rather than taken with respect to a mean density assumed for all of interstellar space, as was done in previous analyses. (Verschuur, 1970, Troland and Heiles, 1982).

4. CALIBRATION USING THE MAGELLANIC STREAM CLOUDS

The Magellanic Stream Cloud data originally drew this author's attention to the Dv-z relationship. According to Lin and Lynden-Bell (1982) the tail of the Stream, where most of these clouds are found, is about 60 kpc from the sun. If we take this to be approximately the same as their effective z-distance then the calibration presented in Figure 1 can be redone. This work gives

$$\log z = \log D_V - 2.71. \qquad (19)$$

Using this Equation, the nT-z and n-z dependences for the clouds were again determined and now found to be given by and

$$\log nT = 3.63 - 0.69 \log z \quad (20)$$

$$\log n = 0.17 - 1.15 \log z. \quad (21)$$

When D_V is derived from Equations 20 and 21 (using Equation 13) we find that

$$\log z = 1.24 \log D_V - 2.11. \quad (22)$$

The diferences between Equations 22 and 23 are smaller than were found between equations 15 and 3 which suggests that the distance calibration using the MSCs is a more valid way to approach these data. In other words, it may be possible to iterate using these parameters to find the best overall agreement. In future a far larger data base and/or a better model for the entire Magellanic Stream will allow a more accurate calibration of the Virial Measure in terms of z-distance and may even reveal second order terms. Verschuur (1986a) will recommend that in the meantime the MSCs be used to set the D_V calibration according to Equation 19.

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