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VELOCITY WAVES IN 21 CENTIMETER SELF-ABSORPTION TOWARD THE TAURUS MOLECULAR COMPLEX

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ABSTRACT

A 10° × 7°.5 region toward the Taurus Molecular Complex has been mapped in 21 cm self-absorption at Arecibo Observatory. The predominant absorption feature, first noted in 1970 by Sancisi and Wesselius, has a systemic velocity of 2.7 km s^{-1}, an apparent axis of rotation close to the galactic plane, and is spun up by a factor of 4 with respect to the predicted value from differential galactic rotation. In contrast, ^{13}CO previously mapped at identical points has a systemic velocity of 6.4 km s^{-1}, and rotates retrograde with respect to galactic rotation with a much higher angular velocity. We suggest that these strange kinematic properties are related to the mysterious origin of Gould's belt, and speculate that the absorbing hydrogen is the wake produced by the supersonic passage of the molecular complex through ambient gas.

A study of the velocity fields of the absorbing hydrogen using Fourier transform techniques reveals significant recorrelations of scale length ~ 16 pc aligned close to the direction of the velocity gradient, and taken along with the data this indicates the presence of velocity waves. Their signature is so clear cut that we suggest they represent a resonance between Alfvén and density waves.

In the direction perpendicular to that of wave propagation, the power spectrum of the velocity field has the appearance of white noise, i.e., having equal energy at all spatial frequencies. This result indicates that any turbulence present has a correlation length smaller than about 0.6 pc.

Subject headings: interstellar: magnetic fields — interstellar: matter — turbulence — wave motions

I. INTRODUCTION

The relationship between the cold, absorbing atomic hydrogen observed at 21 cm in interstellar clouds and the molecular gas inferred from observations of ^{13}CO (McCutcheon, Shuter, and Booth 1978; Levinson and Brown 1980; Peters and Bash 1987) is complex and can be quite variable. To investigate this subject further we observed 21 cm self-absorption on a 41 × 31 rectangular grid in the Taurus Molecular Complex (TMC) that had previously been observed in ^{13}CO (Kleiner and Dickman 1984, 1985). Our major goal was to see whether the ^{13}CO results, namely no resolvable velocity correlations across the region (apart from those caused by rotation), but pronounced column density recorrelations with a scale length of ~ 14 pc, would also apply in the case of the absorbing hydrogen. We find that the 21 cm absorption column density distribution is sufficiently similar to that of the ^{13}CO to suggest that the hydrogen is associated with TMC, rather than being an unrelated foreground feature. In contrast, the velocity field is very poorly correlated with that of the ^{13}CO, and shows some surprising features that we report on briefly in this *Letter*.

II. OBSERVATIONS AND ANALYSIS

Observations were taken in 1985 October with the 1000 foot (305 m) Arecibo[1] telescope, using the 21 cm low sidelobe "flat" feed. The grid of 1271 spectra observed was centered at (1950.0) $\alpha = 04^h30^m$, $\delta = +27°$ ($l = 172°$, $b = -14°$), and aligned parallel to the equatorial coordinates through the center. The angular size of the region mapped was 10° × 7°.5 (24.4 × 18.3 pc for the standard 140 pc distance of TMC), the grid points were separated by 0°.25 (0.61 pc), and the antenna beamwidth was 4′ (0.16 pc). The 260 km s^{-1} velocity range of our data was covered with dual 504 channel spectrometers having a velocity resolution (FWHM) of 1.03 km s^{-1}.

A typical example of an observed spectrum is shown in Figure 1, where the difference between emission and absorption velocities characteristic of the region studied is clearly seen. Velocities for thc absorbing hydrogen were determined in the following way. First, a baseline slope was

[1] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under contract with the National Science Foundation.

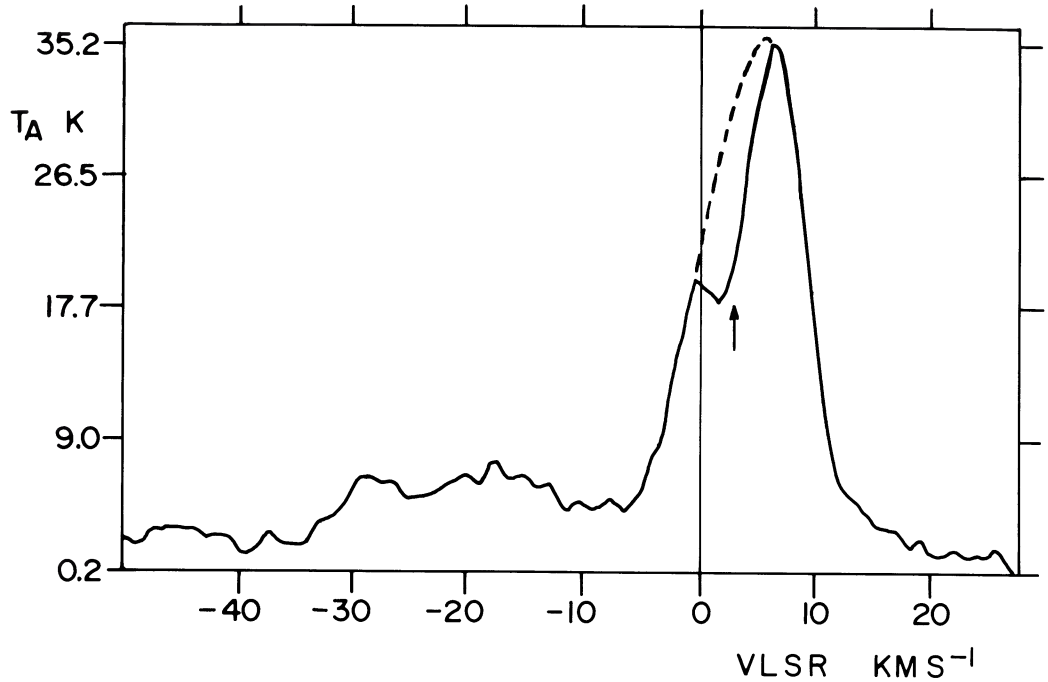

FIG. 1.—The observed 21 cm spectrum at the grid center: (1950) $\alpha = 04^h30^m$, $\delta = +27°$. The arrow at 2.7 km s^{-1} indicates the velocity centroid of the absorption. The emission peak is at 6.5 km s^{-1}. The dashed line represents the interpolating cubic spline used in deriving the absorption.

removed from each 21 cm spectrum. Next, the region of each spectrum where the self-absorption was evident was blanked out, and an interpolating cubic spline was fitted to the emission on either side of this velocity range. Finally, the difference between the data in the absorption region and the spline was taken to give the absorption spectrum. There are a number of locations in our map that exhibit double absorption lines. Secondary features with velocity of ~ 0 km s^{-1} have also been seen by us in ^{12}CO, and optically (White 1984). They are believed to be produced by nearby material and have been suppressed in the present study.

The accuracy of the measured velocities is crucial in assessing the significance of our results. While we have avoided the obvious difficulties listed in a previous study (Levinson and Brown 1980), we attempted to address a number of additional problems that can contribute to velocity errors. These included effects produced by the antenna such as the diameter of the beam and the size and distribution of the near sidelobes, both of which affect the shape of the observed spectrum, and the spectrometer, which we configured to have sufficient velocity coverage to permit proper zero baselines to be determined, and sufficient velocity resolution so that the narrowest absorption lines were not broadened significantly. We also considered errors introduced by our analysis procedure; specifically, the choice of an optimum interpolating function, the possibly of interpreting the dip between two nearby emission peaks as an absorption line, and the difficulties associated with determining the velocity of weak absorption lines. In terms of internal consistency, on the basis of independent analyses of a sample of the data using different procedures, we estimate that a typical value for the maximum velocity error on a single spectrum is ~ 0.8 km s^{-1}.

The field of absorption line velocity centroids is shown in Figure 2*a*. This map shows a gradient running roughly from NE to SW across the grid. Previous work (Scalo 1984; Kleiner and Dickman 1985) has shown that velocity gradients produce spurious features in an autocorrelation analysis. To avoid this, a best-fit planar gradient was subtracted from the observed velocity field. The resulting field is shown in Figure 2*b*. The normalized autocorrelation function

$$\frac{C(\boldsymbol{\tau})}{C(0)} = \frac{\sum \delta v(\boldsymbol{r}) \cdot \delta v(\boldsymbol{r} + \boldsymbol{\tau})}{\sum \delta v(\boldsymbol{r}) \cdot \delta v(\boldsymbol{r})},$$

(where $\boldsymbol{r}$ is a polar coordinate on the grid, $\boldsymbol{\tau}$ is the vector lag, and δv is the velocity deviation from the mean velocity of the field, which is zero after removal of the best-fit plane) was then determined and is shown in Figure 2*c*. The displayed autocorrelation is "biased" (Kleiner and Dickman 1985), meaning that no correction has been made for the reduced number of data points at large vector lags. The most noteworthy feature of Figure 2*c* is the strong recorrelation in centroid velocity with a scale length of ~ 16 pc, seen at position angles (measured from north through east) around 50°.

To help assess the significance of these recorrelations, one-dimensional autocorrelations and their power spectra were computed for the gradient-free velocity data, on straight lines running through the center of the grid at a number of position angles. Even with these subsets of the data, which typically involve only about 40 spectra, highly significant recorrelations are seen at some position angles. In Figure 3 two examples are shown—one in which the recorrelation is insignificant, and one in which it is highly significant.

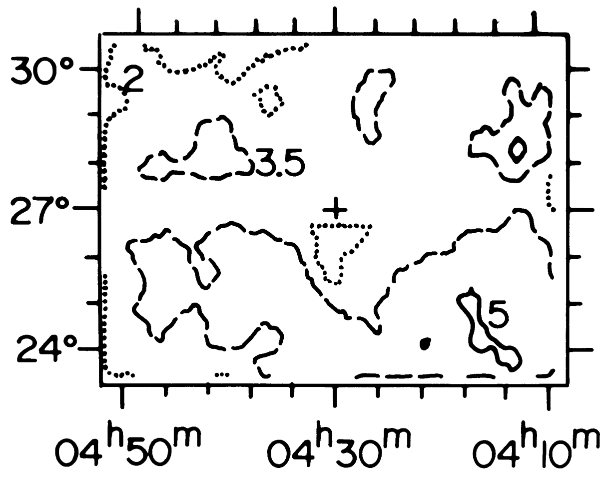

FIG. 2*a*

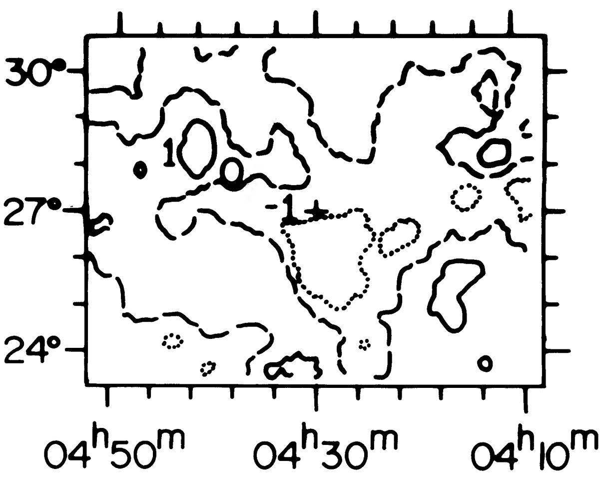

FIG. 2*b*

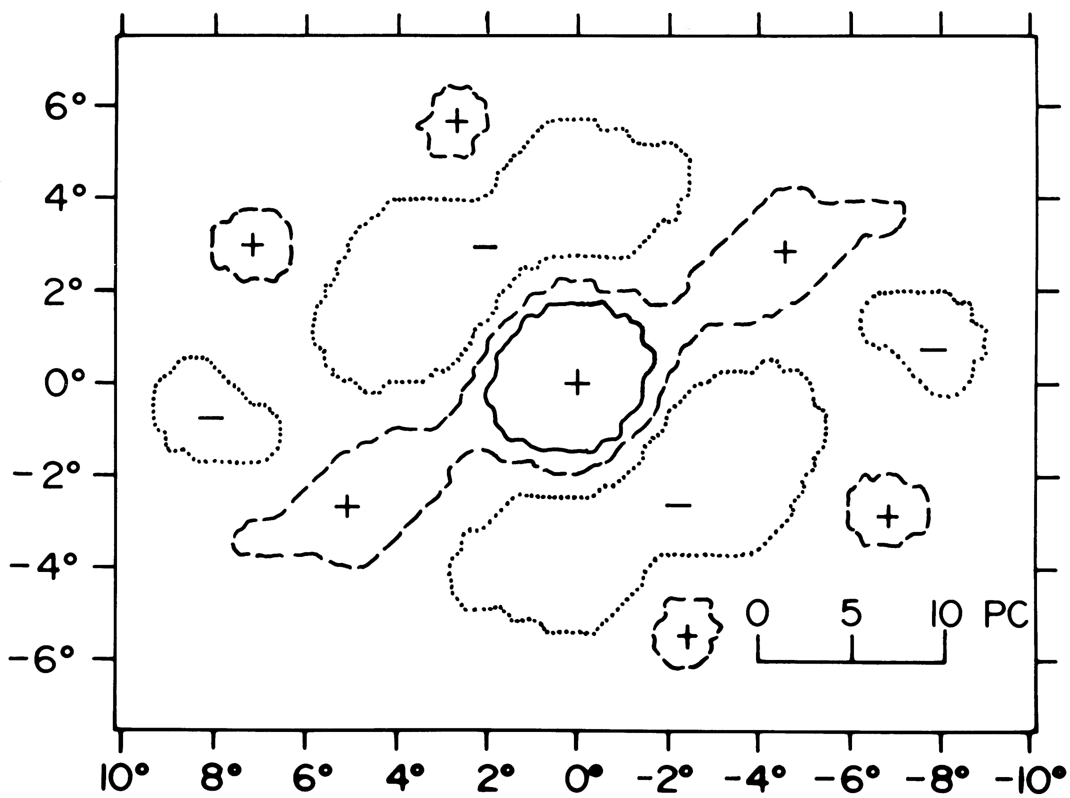

FIG. 2*c*

FIG. 2.—(*a*) The contours of 21 cm absorption velocity centroids as observed (units are km s^{-1}). (*b*) Velocity contours after removal of a best-fit plane. (*c*) The two-dimensional autocorrelation of the velocity field in (*b*). The solid and dashed lines indicate contours of positive correlation, while dotted lines represent negative correlation. The angular scale in the above three figures is the same.

III. DISCUSSION

From the equation of the best-fit plane to the hydrogen absorption velocity field we find the mean velocity to be 2.7 km s^{-1}. The velocity gradient is 85.0 km s^{-1} kpc^{-1}, and if this is interpreted as a rotation the axis is at position angle 297°. These values are listed in Table 1 along with corresponding values for ^{13}CO. Also listed are predictions for these kinematic parameters in the direction $l = 172°$, $b = -14°$ at distance 140 pc arising from standard differential galactic rotation (Oort constant $A = 12.9$ km s^{-1} kpc^{-1}; solar motion components $u_{\odot} = 10.2$, $v_{\odot} = 15.3$, $w_{\odot} = 7.9$ km s^{-1}). We also tabulate predicted values based upon global velocity field fits to 21 cm absorption (Goulet and Shuter 1984) and ^{13}CO

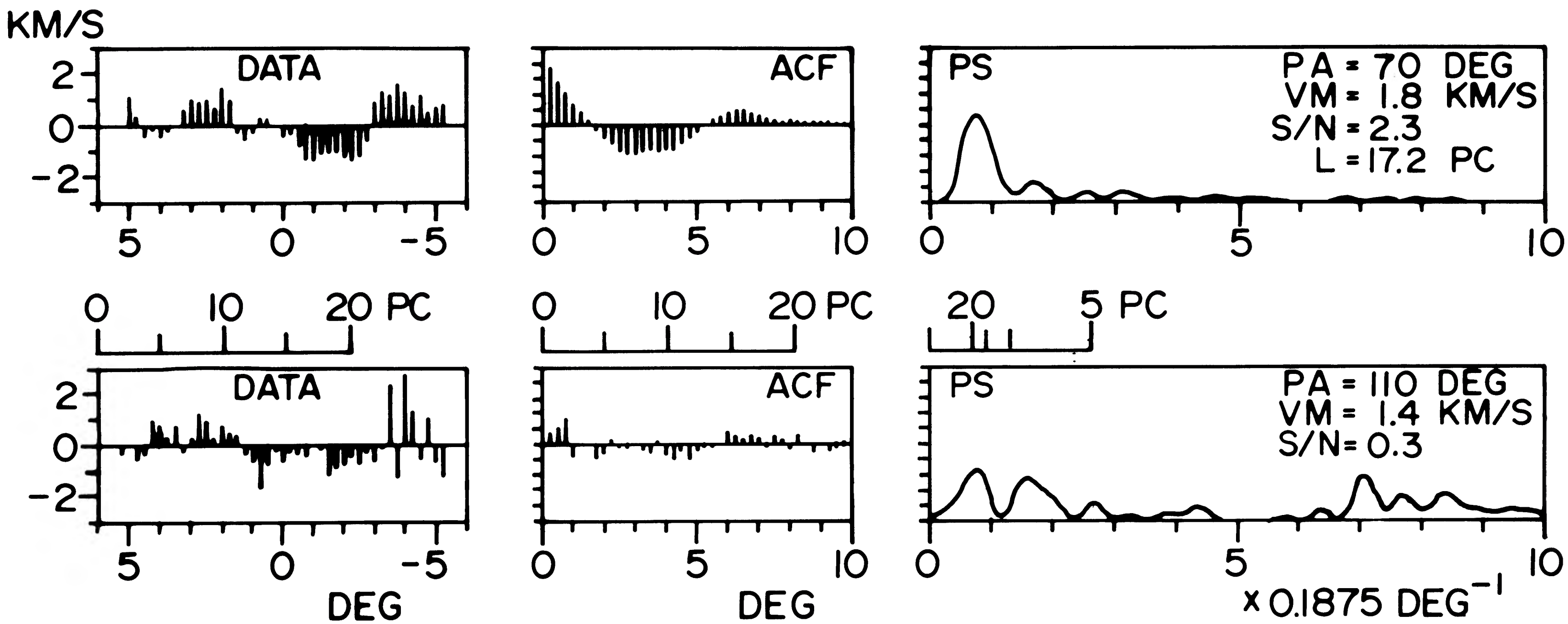

FIG. 3.—Two examples of data, one-dimensional autocorrelation functions (ACF), and their corresponding power spectra (PS) for 21 cm absorption velocities. These were determined from the gradient-free velocity data plotted in Fig. 2*b* for straight lines at position angles (PA) of 70° and 110° passing through the center of the grid. Also indicated are the velocity modulation amplitude (VM) of the largest peak in the power spectrum, the signal-to-noise ratio (S/N) representing the ratio of the energy associated with this peak to that in the rest of the spatial frequency range, and the scale length (L) associated with the peak when this was judged to be significant (i.e., $S/N \geq 1.0$). The intensity scales of the autocorrelations and power spectra, established by injecting high-frequency test sine waves, are the same for both position angles.

TABLE 1

VELOCITIES AND GRADIENTS[a]

Data	Systemic Velocity (km s^{-1})	Magnitude of Gradient (km s^{-1} kpc^{-1})	Position Angle (of inferred rotation axis)
TMC 21 cm absorption	2.7	85	297°
TMC ^{13}CO	6.4	250	25
Global Fit Predictions			
Standard galactic rotation	−0.5	24	227
21 cm absorption	1.6	42	232
^{13}CO	6.3	64	241

NOTE.—For purposes of comparison the magnetic field direction is at position angle 25° (or 205°) (Hemeon-Heyer 1986), the North Galactic pole is at 42°8, and the North pole of Gould's belt at ~ 60° (Taylor, Dickman, and Scoville 1987).

[a] For $l = 172°$, $b = -14°$, and $d = 140$ pc.

emission, the latter calculated from the analysis by Frogel and Stothers (1977).

Table 1 indicates that while the systemic velocities of the absorbing hydrogen and ^{13}CO toward TMC differ significantly—the ^{13}CO is redshifted by 3.7 km s^{-1} with respect to the hydrogen—they are in reasonable accord with the predictions from the global fits. The gradients, however, are completely discordant. Specifically, if interpreted as rotations, the rotation axis of ^{13}CO in the Taurus complex is retrograde with respect to differential galactic rotation (Kleiner and Dickman 1985) and is parallel to the magnetic field direction, while that of the hydrogen is perpendicular. The hydrogen *emission* toward TMC, which we have not yet studied in detail, appears to have a systemic velocity which is a much closer match to the ^{13}CO, as is clearly revealed by the spectrum in Figure 1. This kinematic picture is complex and difficult to account for. We are leaning toward the view that the velocities of hydrogen emission and ^{13}CO, which match Gould's belt velocities (Sodroski, Kerr, and Sinha 1985), are associated with the outward motion of Gould's belt, while the absorbing hydrogen represents a wake in the ambient gas. The apparent retrograde motion of ^{13}CO, previously noted in other molecular clouds and complexes (e.g., Young *et al.* 1981), is possibly explicable in terms of braking either by the magnetic field (Mestel 1965; Mouschovias 1977) or by turbulent viscosity, or it may be the result of gradients in the galactic gravitational potential in the region where the complex was formed (Mestel 1966). These aspects of the large-scale kinematics are discussed in greater detail elsewhere (Shuter and Dickman 1987).

Analysis of the one-dimensional autocorrelations and power spectra taken on lines through the center of the grid, such as the two examples shown in Figure 3, shows that velocity modulation amplitudes are typically ~ 1.5 km s^{-1}. Recorrelation scale lengths range from 9 to 23 pc, and in directions in which the recorrelation is pronounced, there is typically 2–3 times as much energy in the spectral range corresponding to the recorrelation scale as there is at all other scales. In directions in which the recorrelations are insignificant, the power spectra tend to have the appearance of "white noise" (i.e., having roughly equal energy at all spatial frequencies), rather than that of any known form of turbulence spectrum. We believe that most of this noise is produced by random errors in our estimation of velocities and conclude that these data show no evidence of velocity correlation on scales larger than 0°25 (0.61 pc). A similar conclusion was reached in the previous study of ^{13}CO in this region (Kleiner and Dickman 1985). These results strongly suggest that waves, rather than turbulence phenomena, are responsible for the observed velocity recorrelations in the complex.

We interpret our observational data as velocity waves having a peak-to-peak amplitude of ~ 3 km s^{-1}. The evidence for these is based on at least 40 spectra in the one-dimensional velocity analysis, and more than 1000 spectra in the two-dimensional autocorrelation analysis; therefore, the waves clearly dominate the noise produced by our 0.8 km s^{-1} velocity errors. The recorrelation scale length of 16 pc is then taken to be the projected wavelength, and if the complex is planar and inclined at 60° to the line of sight as assumed in previous work (Kleiner and Dickman 1984), the wavelength is 32 pc. If we assume further that the wave velocity is given by $\sqrt{3}$ times the velocity dispersion of the absorption spectra, which is typically ~ 0.6 km s^{-1}, the period of the wave is 3.0×10^7 yr. The rotation period corresponding to the 85.0 km s^{-1} kpc^{-1} velocity gradient that we determined is 7.2×10^7 yr. The similarity of these time scales—which emerge from very different aspects of the observational data—suggests the possibility that the waves are excited by the rotation.

The spatial distribution of the column density of the absorbing hydrogen shows a pronounced central condensation of radius 3.6 pc, with an internal velocity dispersion of 0.60 km s^{-1}. Applying the virial theorem (for a uniform density sphere with surface terms neglected) to this condensation, we obtain

$$3M\sigma_r^2 + (1/2)Mv_A^2 = (3/5)GM^2/R.$$

In the above expression the radius R, and the internal velocity dispersion σ_r, are observed quantities, while the Alfvén velocity v_A, and the total mass M, are unknown. (The kinetic energy associated with rotation of the condensation was found to be negligible and has been omitted.) We solve for the unknowns by assuming equipartition between magnetic and kinetic energy ($v_A^2 = 3\sigma_r^2$), a condition favorable for a resonance between Alfvén and density waves. This gives a total mass M, of 2300 $M_\odot$, a density equivalent to 230 H_2 molecules cm^{-3}; an Alfvén velocity, v_A, of 1.0 km s^{-1}; and a total magnetic field of 1.0×10^{-5} G. The magnetic field value in particular is comparable to recent 21 cm Zeeman effect determinations in the dark cloud L204 (Heiles 1987) which give a maximum value for the line-of-sight component of 10^{-5} G. It should also be noted that if we are observing an Alfvén velocity wave, the position angle of the recorrelations must lie along the projected angle of the magnetic field within the absorbing hydrogen. Observations of starlight polarization in Taurus (Monetti *et al.* 1984), while not entirely clear cut, appear to be consistent with this view.

The presence of velocity waves in some molecular clouds has only recently been recognized. Molecular line and optical polarization studies of L204 (McCutcheon *et al.* 1986) taken together with the 21 cm Zeeman effect observations (Heiles 1987) appear to show behavior similar to the absorbing hydrogen in TMC investigated here. We suggest that the clear signature of velocity waves in our data, taken together with the waves in the column density field (to be discussed in a later publication), indicates that instabilities rather than turbulence are the dominant factor in the formation of molecular clouds within a complex. It also is becoming evident that magnetic fields may play a key role in the process. When we compare the outcome of this study with our original goal we find that while it seems strange that the absorbing hydrogen in TMC appears to have no obvious intimate connection with the ^{13}CO emission, it is even stranger that our two-dimensional autocorrelation of the hydrogen velocity field appears to be almost identical to the corresponding autocorrelation for ^{13}CO column density (Kleiner and Dickman 1984). In that study the scale length was interpreted as a "fossil Jeans length." This work suggests that the fossil is alive, and that the correlations being seen are associated with the present vibrations of magnetic field lines.

IV. CONCLUDING REMARKS

We have found large recorrelation amplitudes in the velocity field of absorbing hydrogen in the Taurus complex. Scale lengths are typically 16 pc, and velocity modulation amplitudes 1.5 km s^{-1}. We interpret these as velocity waves very likely tightly coupled to, or even resonant with, magnetic field line vibrations. These waves dominate the turbulence within the region. We intend in forthcoming studies based on the same data to analyze the 21 cm absorption column densities, to study the 21 cm emission in similar detail, and to attempt to sort out the complex kinematics.

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