DETECTION OF MAGNETIC FIELDS TOWARD M17 THROUGH THE H I ZEEMAN EFFECT

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ABSTRACT

We have carried out VLA Zeeman observations of H I absorption lines toward the H II region in the M17 giant molecular cloud complex. The resulting maps have 60" x 45" spatial resolution and 0.64 km s$^{-1}$ velocity separation. The H I absorption lines toward M17 show between 5 and 8 distinct velocity components, which vary spatially in a complex manner across the source. We explore possible physical connections between these components and the M17 region based on calculations of H I column densities, line-of-sight magnetic field strengths, as well as comparisons with a wide array of previous optical, infrared, and radio observations. In particular, an H I component at the same velocity as the southwestern molecular cloud (M17 SW; $\sim$20 km s$^{-1}$) seems to originate from the edge-on interface between the H II region and M17 SW in unshocked photodissociation region (PDR) gas. We have detected a steep enhancement in the 20 km s$^{-1}$ H I column density and line-of-sight magnetic field strengths ($B_{\text{los}}$) toward this boundary. A lower limit for the peak 20 km s$^{-1}$ H I column density is $N_{\text{HI}}/T_e \geq 5.6 \times 10^{19}$ cm$^{-2}$ K$^{-1}$, whereas the peak $B_{\text{los}}$ is $\sim$ 450 $\mu$G. In addition, blended components at velocities of 11–17 km s$^{-1}$ appear to originate from shocked gas in the PDR between the H II region and an extension of M17 SW, which partially obscures the southern bar of the H II region. The peak $N_{\text{HI}}/T_e$ and $B_{\text{los}}$ for this component are $\geq 4.4 \times 10^{19}$ cm$^{-2}$ K$^{-1}$ and $\sim$ 550 $\mu$G, respectively. Comparison of the peak magnetic fields detected toward M17 with virial equilibrium calculations suggest that $\approx \frac{1}{2}$ of M17 SW’s total support comes from its static magnetic energy, while the other half of its support is supplied by the turbulent kinetic energy (including MHD waves).

Subject headings: H II regions — ISM: clouds — ISM: individual (M17) — ISM: magnetic fields — radio lines: ISM

1. INTRODUCTION

In recent years it has become increasingly clear that magnetic fields play an important role in the process of star formation. (See, for example, Mouschovias & Spitzer 1976; Heiles et al. 1993; McKee et al. 1993). Unfortunately, the experimental techniques for measuring the strength and direction of magnetic fields are few, and these methods are observationally challenging. One such technique uses the Zeeman effect in 21 cm H I absorption lines toward galactic H II regions. Very Large Array (VLA) observations of the Zeeman effect in this line yield maps of the line-of-sight magnetic field strengths ($B_{\text{los}}$). These maps can then be compared to maps of the distribution and kinematics of ionized, atomic, and molecular gas to study the role of magnetic fields in star-forming regions. Moreover, estimates of the masses, column densities, and volume densities of interstellar material associated with the star-forming regions can be compared to field strengths measured via the Zeeman effect. These comparisons are needed to determine the energetic importance of magnetic fields in star-forming regions. For studies of this type, the M17 H II region–molecular cloud complex is ideal, because it has been extensively studied at many wavelengths.

The M17 H II region is one of the strongest thermal radio sources in our galaxy. Its distance has been estimated through photometric and kinematic means to be $\sim$ 2.2 kpc (Chini, Elsässer, & Neckel 1980; Reifenstein et al. 1970; Wilson et al. 1970). There are at least 100 stars in the M17 H II region, with one O4 V (Kleinnmann’s star) and three O5 V stars providing the bulk of the ionizing radiation (Felli, Churchwell, & Massi 1984 and references therein; see Fig. 1). The H II region is made up of two distinct barlike structures, which are $\sim$ 5.7 pc long and $\sim$ 1.1–1.5 pc wide. The southern bar has nearly twice the peak radio continuum flux as the northern bar, and it is located just to the east of the M17 SW molecular cloud core.

The near absence of optical radiation from the southern bar indicates that this region suffers much more optical extinction than the northern bar (Gull & Balick 1974; Fig. 1). Dickel (1968) and Gatley et al. (1979) estimate $A_v \sim 1–2$ mag toward the northern bar. Estimates of the visual extinction toward the southern bar range from $A_v \sim 10$ near the radio continuum peak to $A_v \sim 200$ further west toward the core of the adjacent molecular cloud (M17 SW; Beetz et al. 1976; Felli et al. 1984; Gatley et al. 1979; Thronson & Lada 1983). The low extinction toward the northern bar seems to indicate that the northern molecular cloud, first identified by Lada (1976; $v_{LSR} \sim 23$ km s$^{-1}$), is behind the H II region (Chrysostomou et al. 1992).

The most interesting characteristic of M17 is that the interface between the southern bar of the H II region and M17 SW is seen almost edge-on (see § 3.1). From models of the density gradient on the western edge of the H II region, Icke, Gatley, & Israel (1980) estimated that this interface lies at an angle of $\sim 20^\circ$ with respect to the line of sight. Although the transition from the H II region to the molecular cloud is quite sharp, the interface region is unexpectedly wide in photodissociation region (PDR) tracers such as [C II] 158 $\mu$m (see, e.g., Stutzki et al. 1988). The extended [C II] 158 $\mu$m emission observed in M17 SW by Stutzki et
al. (1988) and Boreiko, Betz, & Zmuidzinas (1990) requires 912–2000 Å UV photons to persist into the molecular cloud at least an order of magnitude further than the predicted UV absorption length scale. That is, atoms are being photoionized and molecules photodissociated further into the molecular cloud than one would expect for a homogeneous medium (see Tielens & Hollenbach 1985 for homogeneous model calculations). A likely explanation for this paradox is that the interface region is clumpy (e.g., Stutzki et al. 1988; Meixner et al. 1992).

Evidence that M17 SW is clumpy has been observed with high angular resolution at many wavelengths. For example, Felli et al. (1984), found clumpiness in their ~10′ resolution radio continuum observations of the M17 H II region. They suggest this clumpiness originates from high-density neutral clumps surrounded by dense ionized envelopes. These clumps may be the remnants of clumps from the parent molecular cloud, which have been overtaken by the H II region ionization front. Massi, Churchwell, & Felli (1988) observed seven clumps in NH₃ emission with 6′ resolution toward the northwestern portion of the H II region–M17 SW interface. The average density and size of these clumps are $n_{\text{H}_2} \sim 10^{5} \, \text{cm}^{-3}$ and 0.05 pc. Stutzki & Güsten (1990) modeled their ~13′ resolution $^{18}\text{O}(2 \rightarrow 1)$ observation (with a larger field of view than the NH₃ observation) with ~179 clumps with average densities of $n_{\text{H}_2} \sim 10^{5}–10^{6} \, \text{cm}^{-3}$ and diameters of ~0.1 pc. Wang et al. (1993) found clumps consistent with the $^{18}\text{O}$ clumps in ~8′–34′ resolution observations of CS and $^{34}\text{S}$ molecules. Hobson (1992) and Hobson et al. (1993, 1994) also saw evidence for clumpiness in HCO⁺, HCN, and $^{17}\text{O}$ molecules and dust emission at ~15′ resolution.

The identification of clumps in M17 SW is significant for several reasons. For example, calculations of density are
more complex because of its dependence on the optical depth of the observed species and the assumed clump filling factor. As discussed previously, the length scale of the PDR also depends on the clumpiness of the region. Therefore, the regions and morphology of photodissociated atomic gas are difficult to predict. Also, the random motion of such clumps can influence observed line widths and the size scale of turbulence within the molecular cloud. These considerations play an important role in our analysis of the H I gas and the line-of-sight magnetic fields calculated from it.

In this paper we report the characteristics of the 21 cm continuum (§ 3.1), H I optical depths and column densities (§ 3.2), and the line-of-sight magnetic field strengths (§ 3.3) derived from our VLA H I Zeeman effect observation. We discuss possible origins for the most prominent H I absorption components in § 4.1. In addition, we present comparisons of our 20 km s$^{-1}$ $B_{\text{ion}}$ map with previous linear polarimetry observations in § 4.2, and we also compare expected magnetic field strengths from virial equilibrium arguments to our observed line-of-sight magnetic field strengths in § 4.3. Our findings are summarized in § 5.

2. OBSERVATIONS

Our H I absorption data were obtained with the DnC configuration of the VLA. Key parameters from this observation can be found in Table 1. We observed both senses of circular polarization simultaneously. Since the Zeeman effect is very sensitive to small variations in the bandpass, we switched the sense of circular polarization passing through each telescope’s IF system every 10 minutes with a front-end transfer switch. In addition, we observed each of the calibration sources at frequencies shifted by ±1.2 MHz from the H I rest frequency to avoid contamination from Galactic H I emission at velocities near those of M17.

The calibration, mapmaking, cleaning, and calculation of optical depths were all carried out using the AIPS (Astronomical Image Processing System) package of the NRAO. The right and left circular polarization data (RCP and LCP, respectively) were separately calibrated and mapped using natural weighting. These two data cubes were then combined to create Stokes I (RCP + LCP) and Stokes V (RCP – LCP) cubes. The I and V cubes were CLEANed using the AIPS task SDCLN down to 70 mJy beam$^{-1}$. Bandpass correction was applied only to the I data, since bandpass effects subtract out to first order in the V data. Subsequent antenna leakage correction and magnetic field derivations were carried out using the MIRIAD (Multichannel Image Reconstruction Image Analysis and Display) processing package from BIMA.

3. RESULTS

3.1. The 21 Centimeter Continuum

Figure 1 shows our 21 cm continuum contours with an optical image from Gull & Balick (1974) and simplified $^{12}$CO contours from Thronson & Lada (1983) superposed. As mentioned previously, the optical nebulosity is only visible toward the eastern side of the H II region because of optical obscuration. Also notice the interface of the H II region with M17 SW on the western side of the southern bar. The total continuum flux at 21 cm is ~800 Jy calculated inside the 1 Jy beam$^{-1}$ (250 K) contour level (lowest contour in Fig. 1). This value is almost twice that obtained by Lockhart & Goss (1978) with a 2’ beam at the Owens Valley interferometer. In addition, we estimate the total flux of the southern bar is 384 Jy, whereas that of the northern bar is 240 Jy (calculated for points inside the 5 Jy beam$^{-1}$ contour level). Our total flux inside the 5 Jy beam$^{-1}$ contour (624 Jy) is similar to the 644 Jy reported by Lada (1976) with the Haystack 37 m telescope and 620 Jy observed by Löbert & Goss (1978) with the Fleurs synthesis telescope at 21 cm.

3.2. Atomic Hydrogen Optical Depths and Column Densities

M17 H I optical depths were calculated assuming that the spin temperature $T_s$ is much less than the background continuum temperature $T_c$ of the H II region. In addition, optical depth calculations were restricted to positions where the continuum power is greater than 1 Jy beam$^{-1}$ (250 K) and the signal-to-noise ratio is higher than 3. The complex nature of the absorption lines in M17 can be seen from the optical depth spectra displayed in Figure 2. The strengths of some components vary spatially over the source but remain distinct, whereas other components seem limited to particular regions. This complexity makes Gaussian fitting very difficult. Our profiles agree qualitatively with the Gaussian fits reported by Lockhart & Goss (1978) made with a 2’ beam and 0.85 km s$^{-1}$ velocity resolution. They fitted their M17 H I optical depth profiles with 8 Gaussians having center velocities ranging from 4.2 to 27.5 km s$^{-1}$. The H I component at ~7 km s$^{-1}$ may correspond to the cold H I cloud (estimated to lie within 150 pc of the sun) observed at this velocity toward the galactic center (Riegel & Crutcher 1972; Crutcher & Lien 1984). In the following analysis we concentrate on the H I velocity component near 20 km s$^{-1}$ and the blended components between 11 and 17 km s$^{-1}$ because of their high optical depths (they contribute the bulk of the H I column density toward the western side of M17) and their coincidence in velocity with other species observed in M17 SW (see § 4.1 for details).

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* Assumes distance of 2.2 kpc.

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Figure 2.—H I Optical depth profiles across the source after convolution with a 2′ beam (each profile is independent). The 1 Jy beam$^{-1}$ 21 cm continuum contour, and 2′ beam are shown for reference.

Figure 3 displays the morphology of the H I optical depths toward the M17 H II region as a function of velocity (every 2 adjacent channels were averaged). A steep increase in the H I optical depths toward the H II region–M17 SW interface is clearly apparent. This effect is particularly noticeable near 20 km s$^{-1}$. Although the H I optical depths become saturated at the western boundary of the H II region (particularly in the northwest), they reach values at least as high as 5. Optical depth maps in the 11–17 km s$^{-1}$ range have their highest values further to the east and in the northern part of the source.

H I column densities toward M17 were calculated using the relationship

$$N_{\text{HI}} = 1.823 \times 10^{18} \tau_v \int \tau_v d\nu \text{ cm}^{-2},$$

where $\tau_v$ is the optical depth per unit frequency. Values for $N_{\text{HI}}/T_v$ summed across the entire H I velocity range, the 20 km s$^{-1}$ component (from 17 to 24.5 km s$^{-1}$), and the 11–17 km s$^{-1}$ blended component are displayed in Figs. 4a, 4b, and 4c, respectively. At positions along the northwest and southwest portions of the source, these maps represent
lower limits to $N_{\text{HI}}/T_e$ owing to saturation effects. Despite this effect, these maps show that the H I column densities are concentrated toward the H II region–M17 SW interface on the southwestern side of the maps. This trend is particularly apparent in Figure 2, where saturated H I optical depth profiles for the 20 km s$^{-1}$ and 11–17 km s$^{-1}$ components lie along much of the western edge of the source. However, this trend is less obvious in the 20 km s$^{-1}$ integrated optical depth map (Fig. 4b), because we set saturated frequency channels to zero in computing the H I column densities. Therefore, regions of highly saturated H I absorption in these maps (for example, along the western side of the source) often do not appear to be optical depth maxima.

There is also spatial agreement between the H I column density concentration prominent in the total $N_{\text{HI}}/T_e$ map (Fig. 4a) near 18$^h$17$^m$30$^s$.0, $-16^\circ$13$'$00", and the northern condensation seen in molecular gas (see Wang et al. 1993; Bergin, Snell, & Goldsmith 1996; and Fig. 13a). The total $N_{\text{HI}}/T_e$ at this position is $8.3 \times 10^{19}$ cm$^{-2}$ K$^{-1}$.

Aside from line saturation, the main source of uncertainty in calculating H I column densities is in the value assumed for $T_e$. Upper limits to $T_e$ for the 20 km s$^{-1}$ H I component come from two sources. For one, the H I line widths in some cases are quite narrow. Toward the southern end of the molecular ridge defined by 19–21 km s$^{-1}$ CS emission (Wang et al. 1993) the 20 km s$^{-1}$ H I line widths are as little

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**Fig. 3.**—Velocity channel maps of the H I optical depth morphology (after averaging every 2 channels) from 6.0 to 25.3 km s$^{-1}$ (gray scale), with contours at $\tau = 1, 2, 3, 4, \text{and} 5$. Notice the increase in H I optical depths as you approach M17 SW in the 24.0–17.6 km s$^{-1}$ velocity range.
as 2.8 km s\(^{-1}\) (see Figs. 10 and 13a). This width implies a maximum 20 km s\(^{-1}\) H\(\text{I}\) temperature of \(\sim 170\) K at this position. Also, along the western periphery of the continuum source (where it overlaps M17 SW), 20 km s\(^{-1}\) H\(\text{I}\) absorption lines exist where the continuum brightness is as little as 250 K (1 Jy beam\(^{-1}\)). Evidently, \(T_e\) is less than about 200 K in many directions toward M17. Also, modeling of \textit{IRAS} 12 \(\mu\)m infrared data by Hobson \& Ward-Thompson (1994) require a hot dust component of \(\sim 108\) K to explain the overall 12 \(\mu\)m emission from M17. This hot dust can be linked to the PDR by the fact that warm emission at 12 \(\mu\)m is likely to arise from a population of polycyclic aromatic hydrocarbons (PAHs; Désert, Boulanger, \& Puget 1990), and PAH emission from PDR regions has been predicted by many authors (e.g., Hollenbach 1993). Evidence that the 20 km s\(^{-1}\) H\(\text{I}\) absorption component is associated with the PDR region is presented in § 4.1.2.

Another indication of the temperature in the atomic gas comes from the observation of [C\(\text{I}\)] 370 \(\mu\)m by Genzel et al. (1988). They estimate a temperature of 50 K for [C\(\text{I}\)] 370
μm gas near 20 km s⁻¹. Molecular temperature determinations may also be relevant if some of the H I is mixed with molecular gas (§ 4.2). Bergin et al. (1994) estimate T_K = 50 K from observations of low-J CO transitions, whereas Harris et al. (1987) show that high-J CO lines (7 → 6, 14 → 13) arise from PDR gas at about 250 K. Meixner et al. (1992) found that the spatial extent and intensities of a wide array of far-infrared and submillimeter cooling lines could be adequately modeled by a three component gas. Their model consists of very dense clumps, n ~ 5 × 10⁵ cm⁻³ and T = 1000 K ([O i] 63 μm, [Si i] 35 μm, and J ≥ 7 CO emission); intermediate-density interclump gas, n ~ 5 × 10³ cm⁻³ and T = 200 K (strong [C i] 370 μm, [C ii] 158 μm, and J ≤ 2 CO emission); and a tenuous extended halo, n ~ 3 × 10² cm⁻³ and T = 80 K (weak extended [C i] 370 μm and [C ii] 158 μm emission). Our 20 km s⁻¹ H I gas most likely resides in the interclump gas, since (1) the narrow 20 km s⁻¹ H I line widths (2.5–5 km s⁻¹) exclude the possibility of it having a temperature as high as 1000 K; (2) the interclump gas is associated with strong [C ii] 158 μm emission, which should coincide with H I in a PDR region (Hollenbach 1993); and (3) the halo component is associated with gas at 23 km s⁻¹ (e.g., Meixner et al. 1992), and gas at this velocity is resolved as a distinct component in our data set. The situation in the 11–17 km s⁻¹ gas is not as clear, since it is wider than the 20 km s⁻¹ component and peaks further east so that a meaningful upper limit to the temperature cannot be set based on its absorption toward the westernmost reaches of the continuum source (see § 4.1.3). Almost certainly, T_K in the H I gas is quite variable, with values in the range 50–200 K most common for the 20 km s⁻¹ component and higher temperatures possible for the 11–17 km s⁻¹ component.

With a spin temperature of 50 K, a lower limit to the peak total column density toward M17 is N_H₂ = 5.1 × 10²¹ cm⁻². Spin temperatures between 50 and 200 K yield peak column densities of (2.8–11.0) × 10²¹ cm⁻² for the 20 km s⁻¹ component and (2.2–9.0) × 10²¹ cm⁻² for the 11–17 km s⁻¹ blended components. We can use estimates of the H I column density to estimate what fraction of the total hydrogen column density arises from atomic gas. For example, Felli et al. (1984) used the optical depth of the silicon absorption feature at 10 μm to estimate that A_v = 30 toward the ultracompact H II region M17 UC1 (18⁰17'32", -16°13'00"). Using N_H₂TOT = 2 × 10²²A_v (Bertoldi & McKee 1992), we estimate that the total column density of hydrogen is N_H₂TOT ≈ 6 × 10²² cm⁻². Our total H I column density toward M17 UC1 is N_HI ≥ 3.7 × 10²¹ cm⁻² (T_K = 50 K). Unless a significant underestimate of T_K or saturation effects have resulted in a severe underestimate of N_HI, much of the gas along the line of sight to M17 UC1 is in the form of H₂.
3.3. Magnetic Field Strengths From the Zeeman Effect

The H I Zeeman effect is only sensitive to the line-of-sight magnetic field ($B_{\text{los}}$) in most astrophysical situations, since the Zeeman splitting is a tiny fraction of the line width. Since $V \ll dI/dv$, values for $B_{\text{los}}$ were obtained by fitting the derivative of the I profile to the V profile at each pixel with a least-squares fitting routine (for details, see Roberts et al. 1993; Crutcher et al. 1996). Because of the complexity of the H I spectra, the number of channels fitted for each velocity component is small. To obtain more realistic error estimates, 40 channels outside of the line region were included in each fit. Note that, although $B_{\text{los}}$ maps were attempted using synthetic I profiles generated by Gaussian analysis of the data, they did not show significant improvements in either the fit or error estimates, so they were abandoned. All of the magnetic field maps presented in this paper show values of $B_{\text{los}}$ where the fit is judged significant, that is, where $B_{\text{los}}/\sigma(B_{\text{los}}) > 3$. (The quantity $B_{\text{los}}/\sigma(B_{\text{los}})$ is henceforth denoted $S/N_B$.) The maps also show values of $B_{\text{los}}$ where $\sigma(B_{\text{los}}) < 15 \mu G$ even if the first criterion is not met. This later criterion insures that fit values are displayed where the data establish that $|B_{\text{los}}|$ is small. Finally, the maps show fit values only where the continuum brightness exceeds 1 Jy beam$^{-1}$. Given these selection criteria, blank areas in the magnetic field maps represent regions for which no useful information is known about $B_{\text{los}}$. For example, $B_{\text{los}}$ may actually be quite large in some blank regions, yet the fit is insignificant owing to the blending of adjacent line components or to the weakness of the absorption lines.

3.3.1. Magnetic Fields Derived for the 20 km s$^{-1}$ Component

A significant magnetic field exists in the 20 km s$^{-1}$ component over much of the central region of the southern bar. The velocity range of the fit for this component is 17.0–24.6 km s$^{-1}$. This range includes a separate H I component near 23 km s$^{-1}$, which was also detected by Lada & Chaisson (1975) in H$_2$CO and has been associated with a tenuous halo of gas that is obscuring part of M17 (Meixner et al. 1992; § 3.2). A map of $B_{\text{los}}$ for the 17–24.6 km s$^{-1}$ velocity range is shown in Figure 5, and sample fits at representative pixels are shown in Figs. 6a–6c. Negative values indicate that $B_{\text{los}}$ is toward the observer. Careful inspection of the data cube suggests that the values of $B_{\text{los}}$ shown in Figure 5 apply only to the 20 km s$^{-1}$ component (based on the velocity where the Stokes V profile changes sign; see, for example, Figs. 6a–c). In fact, wherever the 23 and 20 km s$^{-1}$ components are significantly blended (for example, toward the northern condensation), no values of $B_{\text{los}}$ could be derived. Values of $B_{\text{los}}$ that meet our selection criteria (§ 3.3) are centered near the continuum peak of the southern bar. The values for $B_{\text{los}}$ start out at $\sim -100 \mu G$ on the eastern side of the southern bar, pass through a shallow saddle point, and then rapidly rise to $\sim -450 \mu G$ on the western side of the map near the H II region–M17 SW interface. The maximum $S/N_B$ obtained for this component is 8.5.

3.3.2. Magnetic Fields Derived for the Blended 11–17 km s$^{-1}$ Components

Strong, primarily positive magnetic fields were also detected for the blended velocity components between 11 and 17 km s$^{-1}$. A map of this magnetic field is shown in Figure 7, and the fit to a few representative pixels can be seen in Figures 8a–8c. There are four main regions of significant $B_{\text{los}}$ for this blended component, which appear

![Figure 6](image_url)

**Figure 6**—Representative fits at three positions for the 20 km s$^{-1}$ component (17.0–24.6 km s$^{-1}$). The upper panels show Stokes I profiles (dashed histogram), and the bottom panels show Stokes V profiles (solid histogram), with the fitted derivative of Stokes I shown as a smooth dashed curve. In the upper and lower panels, the velocity range used in the fit is denoted by solid or heavier lines. The value of $B_{\text{los}}$ fitted for each position and its calculated error are given at the top of each plot. (a) Position 18$^\text{h}$17$^m$35$^s$, $-16^\circ14^\prime00^\prime$. (b) Position 18$^\text{h}$17$^m$30$^s$6, $-16^\circ14^\prime00^\prime$, also known as position ($-60$, -30) in Stutzki et al. (1988). (c) Position 18$^\text{h}$17$^m$28$^s$5, $-16^\circ14^\prime16^\prime$, also known as position ($-90$, -45) from Stutzki et al. (1988).
primarily in the northeastern, north-central, and western parts of the map. The center velocity of this component (defined by the velocity at which the derivative changes sign) is somewhat different in each of these regions. They range from 14.4 km s$^{-1}$ in the northeast (Fig. 8a) to 13.7 km s$^{-1}$ in the central northern feature (Fig. 8b) to 14.0 km s$^{-1}$ in the northwest (Fig. 8c) to 12.4 km s$^{-1}$ in the southwest. The $B_{\text{los}}$ in the northwestern feature reaches values as high as 550 $\mu$G with $S/N$ as high as 14.

4. DISCUSSION

4.1. Proposed Origin of Magnetic Field Components

Meixner et al. (1992) suggest that the M17 H II region is carving a bowl into the molecular cloud to the southwest (M17 SW). This suggestion is based on the coincidence of part of their [O I] 63 $\mu$m emission with the southern bar of the M17 radio continuum. The symmetry axis of the bowl lies in the plane of the sky, and the overlapping [O I] 63 $\mu$m emission arises from a PDR on the front and/or back sides of the bowl. The bottom of the bowl (at the southwestern edge of the southern bar) is the portion of the H II region--M17 SW interface viewed edge-on, and the high visual extinction observed toward the southern bar arises from the front side of the molecular bowl. Gull & Balick (1974) also suggest a bowl morphology based on H76a radio recombination line profiles that have double peaks separated by $\sim$20 km s$^{-1}$. The centroids of these double-peaked profiles are close to the systemic velocity of the M17 H II region ($\sim$18.6 km s$^{-1}$), and they are thought to arise from streaming motions of newly ionized gas at the front and back sides of the bowl (see also Goudis & Meaburn 1976; Clayton et al. 1985). In short, it seems likely that the western side of the H II region is partially embedded in and partially obscured by a bowl of clumpy neutral gas (§ 1). The region may closely resemble the scenario discussed by Bertoldi & Draine (1996), in which dense clumps are slowly photodissociated by a nearby H II region.

In many ways, this M17 interface model resembles the interface region between the Orion nebula and the molecular cloud behind it. For Orion, the interface lies in the plane of the sky with the ionizing stars directly in front of it. For M17, the geometry is turned by 90°. The interface layer is perpendicular to the plane of the sky, with the ionizing stars offset to the northeast. The densest accumulation of ionized gas in M17 lies along the “working surface” near the ionization front. Therefore, the brightest region in the M17 continuum map, the southern bar, does not coincide in the sky with the ionizing stars as it does for the Orion nebula.

The edge-on orientation of the M17 H II region--M17 SW interface offers a rare opportunity to observe the relative locations of PDR species. These observations can then be compared with predictions of simple planar PDR models.
Fig. 8.—Same as Figs. 6a–6c except the range of velocities used in the fit for $B_{nw}$ was 11–17 km s$^{-1}$. (a) Northeastern position 18$^h$17$^m$40$^s$.6, $-$16$^h$10$^m$15$^s$. (Fig. 7; white plus symbol). (b) North-central position 18$^h$17$^m$35$^s$.6, $-$16$^h$10$^m$51$^s$. (Fig. 7; black plus symbol). (c) Northwestern position 18$^h$17$^m$28$^s$.7, $-$16$^h$09$^m$12$^s$. (Fig. 7; white plus symbol).

Fig. 9.—H I optical depth profile (present work) and a [C II] 158 μm spectra from Boreiko et al. (1990; 43′ resolution) for the position of the Stutzki et al. (1988) [C II] 158 μm peak, 18$^h$17$^m$32.5, $-$16$^h$13$^m$42′, or (−30,−15).

To facilitate such a comparison, Stutzki et al. (1988) define a northeast-southwest strip across the interface region ($\Delta \delta = \Delta \alpha/2$). This strip runs perpendicular to the interface; ionizing radiation propagates northeast to southwest. These authors plot relative (velocity-integrated) emission from several PDR tracers across this strip. They find that the progression from ionized to atomic to molecular gas qualitatively agrees with simple planar PDR models. However, the width of the interface region is broader than expected from homogenous planar models. This discrepancy likely arises from clumpiness in the region (§1).

Besides H I absorption, another important tracer of atomic gas in PDR regions is [C II] 158 μm emission. (See review by Hollenbach 1990.) Matsuhara et al. (1989) present a velocity-integrated map of this emission toward M17. Although the spatial resolution of the Matsuhara et al. map is low (3′4′), the morphologies of velocity-integrated [C II] 158 μm emission and H I absorption (Fig. 4a) are quite similar. This correspondence strongly suggests that the H I absorption is closely associated with the PDR region.
However, the velocity structure of the two atomic tracers is different. Figure 9 presents an H I optical depth profile and a [C II] 158 μm emission profile (Boreiko et al. 1990) for the same position in the interface region. Differences in the two profiles may arise from the tendency of [C II] 158 μm emission and H I absorption to preferentially sample warm and cool gas, respectively.

In the two subsections below, we argue that H I gas near 20 km s\(^{-1}\) and also in the range 11–17 km s\(^{-1}\) has been photodissociated by the M17 H II region. We suggest that the 20 km s\(^{-1}\) gas is unshocked by the H II region and very closely associated with molecular gas. We also suggest that H I in the range 11–17 km s\(^{-1}\) arises from shocked gas streaming toward us from the front side of the molecular bowl. The association of different H I absorption components with shocked and unshocked gas has also been suggested for S106 (Roberts, Crutcher, & Troland 1995) and W3 (Roberts et al. 1993).

4.1.2. The Nature of H I Gas at 20 km s\(^{-1}\)

The 20 km s\(^{-1}\) H I component is most prominent along the western and southwest sectors of M17. It is rather narrow (2.5–5 km s\(^{-1}\)), and its center velocity changes little with position along the interface region. In addition, much of the molecular emission toward M17 is at velocities near 20 km s\(^{-1}\) (e.g., Rainey et al. 1987). Figure 10 shows an H I optical depth profile and several molecular emission profiles from Stutzki et al. (1988) for a position at the H II region–M17 SW interface. Note the similarity in the center velocities of each species near 20 km s\(^{-1}\). Also striking is the similarity between 20 km s\(^{-1}\) H I optical depth profiles and CS emission profiles toward the CS molecular ridge observed by Wang et al. (1993; Fig. 11). The line widths for both species are very narrow, and their center velocities correspond closely. The narrowness of these lines suggest that the 20 km s\(^{-1}\) H I and molecular gas toward this region are unshocked by the M17 H II region (see also Wang et al. 1993). The velocity coincidence at 20 km s\(^{-1}\) toward M17 SW strongly suggests that this H I component is closely associated with the M17 SW molecular core, most likely arising in the PDR at the H II region–M17 SW interface. If so, values of \(B_{\text{los}}\) derived from the H I Zeeman effect at 20 km s\(^{-1}\) are of direct relevance to the energetics of M17 SW and its immediate surroundings.

Further indications of the locale of the 20 km s\(^{-1}\) H I gas come from its distribution along the northeast-southwest strip of Stutzki et al. (1988). In Figure 12, we plot some of the Stutzki et al. data (upper panel) and also results from our H I absorption observations where profiles are not saturated (lower panel). The rise in \(N_{\text{H I}}/T_s\) for the 20 km s\(^{-1}\) H I component most nearly matches the rise in \(^{12}\text{CO} J = 7 \rightarrow 6\) and 2 \(\rightarrow\) 1 emission. This coincidence provides further evidence of an association between 20 km s\(^{-1}\) H I and molecular gas. Also, the rise in 20 km s\(^{-1}\) \(N_{\text{H I}}/T_s\) appears to place this atomic gas between the H II region (to the left) and the bulk of the molecular gas as traced by \(^{18}\text{O} (J = 2 \rightarrow 1)\) emission (to the right). Such a progression from ionized to atomic to molecular gas is, of course, expected in a PDR.
same region lies just to the east of the central condensation defined by the optically thin, high-density tracer HC$_3$N ($J = 4 \rightarrow 3$; Bergin et al. 1996). Note that the sharp edge seen on the western side of the $20 \text{ km s}^{-1}$ $B_{los}$ map comes from our masking criteria. The fact that these two high-density tracers show a somewhat different emission morphology is most likely a consequence of excitation effects, since the temperature ranges from 50 K at the interface to 30 K further west (Bergin et al. 1996). Similar morphological differences were observed by Bergin et al. (1997) for a large number of molecular transitions. Nonetheless, the density throughout the region mapped by the combination of CS and HC$_3$N emission shows remarkably little variation ($n_{H_2} \sim 10^5 \text{ cm}^{-3}$; Bergin et al. 1996). Therefore, the CS and HC$_3$N maps taken together should delineate reasonably well the full extent of high-density material in M17 SW. Figures 13a–13b clearly show that the $20 \text{ km s}^{-1}$ $B_{los}$ increases toward the high-density regions west of the interface.

The close association between H I gas (and $B_{los}$) near $20 \text{ km s}^{-1}$ and the molecular ridge region could arise in at least two ways. For one, the H I may be well mixed with and a minor constituent of the molecular gas. In such a case, the Zeeman effect near the CS ridge (Fig. 13a) is directly representative of magnetic fields in the molecular gas. A second possibility is that the absorbing H I gas near $20 \text{ km s}^{-1}$ is confined to a thin photodissociated shell about the molecular ridge or to thin shells surrounding a multitude of molecular clumps within the ridge. In this case, the H I Zeeman effect is also representative of the magnetic field in the molecular gas if the H I is photodissociated but dynamically undisturbed H$_2$.

In either case, the H I Zeeman effect near the molecular ridge must arise in relatively dense gas if approximate equilibrium exists between the magnetic energy density and that associated with nonthermal motions in the gas. Such an equilibrium was suggested by Myers & Goodman (1988a, 1988b, 1991) and Bertoldi & McKee (1992) on the basis of limited observational data and from theoretical considerations by Mouschovias & Psaltis (1995; see also § 4.3). Under this assumption, the gas density is given by

$$n_{eq} = \frac{B}{0.4\Delta v_{NT}} \text{ cm}^{-3},$$

where $n_{eq}$ is the proton density, $B$ is the average total field strength ($\mu G$), and $\Delta v_{NT}$ is the FWHM contribution to the line width from nonthermal motions ($\text{km s}^{-1}$; see also § 4.3). As an example we apply this equation to the position of Figure 10, about $15^\circ$ east of molecular ridge. At this position, $\Delta v \approx 4 \text{ km s}^{-1}$, and $B \gtrsim 200 \mu G$. If $T_F = T_K = 50–200$ K (see § 3.2), $\Delta v_{NT} = 3.7–2.6 \text{ km s}^{-1}$, and $n_{eq} \gtrsim (2–4) \times 10^4 \text{ cm}^{-3}$. This estimate of the local density in which the H I Zeeman effect arises is conservative, since the actual total field strength almost certainly exceeds $B_{los}$ and $n_{eq} \propto B^2$.

However, $n_{eq}$ is in excellent agreement with the density $n_{eq} \approx 6 \times 10^4 \text{ cm}^{-3}$ calculated toward M17 SW by Goldsmith, Bergin, & Lis (1997) using $^{18}$O column densities, a $2 \text{ pc}$ linear extent, and 47" resolution. Significantly higher densities have been estimated in M17 SW (i.e., Hobson et al. 1993 using dust continuum, Wang et al 1993 using CS, and Bergin et al. 1996 using HC$_3$N, to name a few with $n_{H_2} \sim 10^5–10^6 \text{ cm}^{-3}$). Nonetheless, the estimate by Goldsmith et al. is likely to be the most accurate estimate of the mean
density of M17 SW since it does not suffer from assumptions of temperature or selection effects due to critical density requirements.

If the H I Zeeman effect arises in a gas having $n_{eq} \approx (2-6) \times 10^4$ cm$^{-3}$, then H I represents only a small fraction of the neutral gas along the line of sight. For example, at the position of Figure 10 we have $N_{HI} = (1.5-6.0) \times 10^{21}$ cm$^{-2}$ for $T_e = 50-200$ K. Using the same depth for M17 SW (2 pc) as Goldsmith et al. (1997), $n_H \approx 250-1000$ cm$^{-3}$. One possibility is that H I amounts to about a 1%-5% constituent of largely molecular gas. Alternatively, H I might not be mixed with H$_2$ but confined to thin, dense atomic envelopes surrounding the molecular clumps observed in the interface region (see §1). Note that this would still require the H I gas to occupy about 1%-5% of the line of sight in the absorbing region. These two cases are the same ones cited above to explain the close association of H I gas with molecular gas in M17 SW.

4.1.3. The Nature of H I Gas at 11–17 km s$^{-1}$

The 11–17 km s$^{-1}$ H I gas is primarily distributed in an arc that partially encircles the northern and southern bars of the H II region (Figs. 3 and 4c). This arc corresponds well with a similar arc structure apparent in $^{12}$CO and $^{13}$CO emission in this velocity range (Lada 1976; Rainey et al. 1987; Stutzki et al. 1988; Greaves, White, & Williams 1992). At several positions, the velocity correspondence between H I and molecular gas is excellent. For example, toward the southwestern region of our 11–17 km s$^{-1}$ magnetic field map (Fig. 7), where the H I line center is 12.4 km s$^{-1}$, Greaves et al. (1992) find $^{12}$CO and $^{13}$CO emission centered at 12 km s$^{-1}$. Also, Massi et al. (1988) observed that two of their seven NH$_3$ clumps near M17 UC1 have velocities of 15.5 km s$^{-1}$, and Stutzki et al. (1988) observed C$^{18}$O clumps in the 11–17 km s$^{-1}$ velocity range. Blueshifted [C II] 158 $\mu$m emission has also been observed in this velocity range (Boreiko et al. 1990; Fig. 9).

Despite the existence of molecular gas in the 11–17 km s$^{-1}$ range, the overall association between H I and molecular gas is much less clear than it is at 20 km s$^{-1}$. Toward the northern bar in particular, where the 11–17 km s$^{-1}$ H I magnetic fields are high (see §3.3.2; Fig. 7), there is not always a molecular counterpart in the 11–17 km s$^{-1}$ velocity range. In fact, for the positions shown in Figures 8a and 8b there is little evidence of molecular gas. Apparently, the density of molecular material in this region is low compared to the western interface. This lack of spatial agreement can also be seen from the distribution of 11–17 km s$^{-1}$ $N_{HI}/T_e$ across the Stutzki et al. strip scan (Fig. 12). Unlike the 20 km s$^{-1}$ H I component, the 11–17 km s$^{-1}$ $N_{HI}/T_e$ rises east (to the left) of the molecular data. A variable ratio of atomic to molecular gas might be expected if gas in this velocity range has been subjected to a widely variable degree of dissociation in the interface region. Also, the 11–17 km s$^{-1}$ H I gas is blueshifted by 2–8 km s$^{-1}$ relative to the H II region center velocity of ~19 km s$^{-1}$ (Joncas & Roy 1986). The morphology and complex velocity structure of H I gas between 11–17 km s$^{-1}$ (Figs. 2 and 8a–8c) suggests that it lies on the near side of the bowl described in §4.1.1 and has been shocked and accelerated away from the ionized gas.

Several reasons exist to expect H II region–driven motions of a few km s$^{-1}$ near M17. Observationally, Rainey et al. (1987) fitted their $^{13}$CO data on molecular clumps near the southern bar to a geometric expansion model about Kleinmann’s star (Fig. 1). They obtain an expansion velocity of $\approx 11$ km s$^{-1}$ about this star. While polarimetry studies do not show clear evidence for a simple expansion model (Vallée & Bastien 1996), the Rainey et al. analysis still provides a useful estimate for the magnitude of shock speed, which can be driven by the M17 H II region. Radio and optical recombination line observations often reveal split profiles shifted by about $\pm 8$ km s$^{-1}$ from the H II region rest velocity (Gull & Balick 1974; Goudis & Meaburn 1976; Clayton et al. 1985; Joncas & Roy 1986).
Theoretically, Bertoldi & Drain (1996) estimated the shock-induced acceleration expected in the Orion nebula PDR, obtaining a value of 3 km s\(^{-1}\). This value is somewhat sensitive to the ratio of post to preshock density, taken by Bertoldi & Drain (1996) as 2\([\rho_{\text{post}}/\rho_{\text{pre}}] = (\Delta v_{\text{post}}/\Delta v_{\text{pre}})^2\). If the ratio for M17 is 4, as suggested by the \(^1\)CO (7 → 6) line width (5 km s\(^{-1}\); Harris et al. 1987) and the CS (2 → 1) line width (2.5 km s\(^{-1}\); Wang et al. 1993), then the shock-induced acceleration is increased to 6 km s\(^{-1}\).

Also, Bertoldi (1989) and Bertoldi & McKee (1990) discuss a rocket effect upon ablating clumps of neutral gas exposed to ionizing radiation. They estimate that rocket acceleration should amount to a clump velocity of 5–10 km s\(^{-1}\) under typical circumstances. These estimates of shock speed agree quite well with the 2–8 km s\(^{-1}\) blueshift of the 11–17 km s\(^{-1}\) H\(\alpha\) components.

Although molecular column densities are low in the 11–17 km s\(^{-1}\) range, H\(\alpha\) field strengths are very high, reaching values of over +500 \(\mu\)G (Fig. 7). Therefore, the assumption of equilibrium between magnetic and nonthermal energies leads to conclusions similar to those for gas near 20 km s\(^{-1}\) (§ 4.1.2). That is, \(n_{\text{col}} > 10^4\) cm\(^{-3}\), and \(n_{\text{H}}\), averaged along the line of sight is about 2 orders of magnitude less than \(n_{\text{col}}\). Yet the scarcity of molecular gas at positions of high field strength means that H\(\alpha\) at these positions cannot exist as a minor constituent in a largely molecular region. If the H\(\alpha\) alone is to exist at a density near \(10^4\) cm\(^{-3}\), it must reside in one or more thin layers that occupy only about 1%–5% of the path length through the H\(\alpha\) absorbing region. That is, the absorbing H\(\alpha\) gas must be distributed in a very clumpy fashion along the line of sight. This conclusion is consistent with numerous other indications of a highly clumped medium in the M17 region (§ 1).

Most likely, the absorbing H\(\alpha\) gas is shocked, photodissociated gas lying in thin interface regions about ablating neutral clumps. The clumps, in turn, lie within mostly ionized gas, like the clumps modeled by Bertoldi & Drain (1996) or the clumps identified by Felli et al. (1984) in high-resolution M17 radio continuum maps. In these clumps, the pressure of the ionized gas drives a shock front into the neutral medium. Therefore, a rough equivalence between the thermal energy density of the ionized gas and the magnetic energy density in the adjacent compressed atomic region is expected. If the M17 ionized gas has a temperature of 8000 K (Subrahmanyan & Goss 1996) and a density of 10\(^4\) cm\(^{-3}\) (Felli et al. 1984), then its thermal energy density is equivalent to the magnetic energy density in the thin H\(\alpha\) layers for \(B \approx 500\) \(\mu\)G.

### 4.2. Comparison of 20 km s\(^{-1}\) \(B_{\text{los}}\) Field Morphology with Polarimetry Studies

A number of studies have been made of linear polarization toward M17. These include polarimetry at optical and near-IR wavelengths from grain absorption and polarization in the far-IR from grain emission (see references cited by Dotson 1996). Such studies reveal the position angles of the magnetic field in the plane of the sky (\(B_\parallel\)), but they yield little if any information about field strengths. Therefore, they complement Zeeman effect studies, assuming the linear and circular polarization arise in the same regions. In general, field directions inferred from grain absorption do not agree with those inferred from grain emission. Very likely, this discrepancy results from the different regions sampled by each technique, with grain emission data more likely representative of the field directions inside M17 SW (Goodman et al. 1995). Therefore, we restrict our comparisons to polarimetry derived from grain emission observations.

The study of polarized 100 \(\mu\)m dust emission by Dotson (1996) provides the most comprehensive data set available for comparison with H\(\alpha\) Zeeman effect results. In Figure 14 we present a map of the position angle of the plane of sky magnetic field \(B_\parallel\) from Dotson (1996) overlaid on our \(\sim 20\) km s\(^{-1}\) \(B_{\text{los}}\) gray scale. The resolution of the Dotson study (35") is comparable to that of the H\(\alpha\) data. A principal conclusion of the Dotson study is that the M17 magnetic field shows a significant degree of spatial coherence across M17. The H\(\alpha\) Zeeman data for the 20 km s\(^{-1}\) component corroborates this result (Figs. 5, 13a, and 13b). Moreover, the eightfold increase in \(B_{\text{los}}\) from east to west toward the molecular ridge (Fig. 13a) is matched by a decrease in fractional linear polarization from about 4% to 1%. Along this same line the field has a nearly constant position angle (predominantly east-west). Unfortunately, no comparison can be made toward the 100 \(\mu\)m dust peak (toward the northern condensation) where very little polarization was measured, because we were not able to detect a 20 km s\(^{-1}\) \(B_{\text{los}}\) in this region (see § 3.3.1).

One obvious interpretation of the 100 \(\mu\)m polarimetry and H\(\alpha\) Zeeman data is that the magnetic field lines curve into the line of sight as one approaches M17 SW from the east. In such a case, \(B_{\text{los}}\) may be a close approximation to the total field strength in the region of M17 SW sampled by H\(\alpha\). Since the H\(\alpha\) must lie in front of the H\(\pi\) region, the field lines in this picture wrap around the H\(\pi\) region on the front side of the bowl, becoming more aligned with the line of sight at the bottom of the bowl as they pass through the molecular ridge (defined by CS in Fig. 13a). This geometry is consistent with the inferences made by Dotson from the linear polarization data alone. The origin of the field curvature may lie in the process of gravitational contraction that formed M17 SW, gathering an initially uniform field along the line of sight into an hourglass shape with M17 SW at its waist. This picture is also supported by the fact that the 100 \(\mu\)m linear polarization percentage increases again west of the densest part of the M17 SW core (Figs. 13b and 14). Hourglass-shaped field structures were also suggested for the W3 region by Roberts et al. (1993) and OMC-1 by Schleuning (1998).

It is also possible that the occurrence of decreasing linear polarization toward the 100 \(\mu\)m flux and column density maxima could result from effects other than field geometry. For example, optical depth effects, variations in dust properties, grain alignment efficiency, or some combination of these effects could cause a decrease in the linear polarization independent of the magnetic field. Alternatively, the magnetic field itself could simply be more tangled in higher density regions (Jones, Klebe, & Dickey 1992; Myers & Goodman 1991).

A second dust emission polarization study toward M17 is that of Vallée & Bastien (1996) at 760 \(\mu\)m. This study is significantly different from that of Dotson (1996), because it samples cooler gas, the angular resolution is much higher (14"), and the only positions included in the study were the six main dust peaks of M17 SW. These dust peaks are shown in Hobson et al. (1994) to be well correlated with the high-density tracer \(^{13}\)CO and with embedded far-IR sources for positions P1–P3 (located in the northern
condensation). The polarizations reported by Vallée & Bastien for positions P4–P6 (toward the central region of M17 SW) are comparable to those measured by Dotson, and are also consistent with our suggestion that the highest values of the 20 km s$^{-1}$ $B_{\text{los}}$ arise in regions where the magnetic field is nearly in the line of sight. For example, P4 lies within our region of high-$B_{\text{los}}$ ($\sim -350$ $\mu$G), and the polarization percentage is only 0.15%, compared to the 2% average. However, toward the northern condensation (P1–P3), Vallée & Bastien (1996) detect significant linear polarization, where Dotson detected little if any. This discrepancy between the two linear polarization studies could arise from differences in sampling (spatially or along the line of sight) and may point to significant fluctuations in magnetic field direction in the northern condensation. However, it is also possible that the differences are merely a result of wavelength-dependent grain optical properties. Polarimetry of this region at 350 $\mu$m from CSO (D. A. Schleuning 1998, private communication) and higher resolution H I Zeeman results (Brogan et al. 1999) may help to clarify this issue.

### 4.3. Magnetic Energy versus Turbulent and Gravitational Energy

The magnetic field in a cloud can be separately described in terms of a static component $B_S$ and a time-dependent or wave component $B_w$, each of which can in principle contribute to the observed $B_{\text{los}}$ and $B_\perp$. The static component connects the cloud to the external medium and also determines the total magnetic flux through the cloud, whereas the wave component is associated with MHD waves in the cloud (e.g., Arons & Max 1975). Although the static component of the field can only provide support to the cloud perpendicular to the field lines, the turbulent or wave component can provide three-dimensional support (McKee & Zweibel 1995 and references therein). It is likely that Zeeman effect ($B_{\text{los}}$) and polarimetry ($B_\perp$) studies are primarily indicative of the magnitude and direction of $B_S$. This conclusion applies if the length scale over which $B_w$ maintains a constant direction is significantly smaller than the size of the cloud (Myers & Goodman 1991). In such a case, spatial averaging over the beam and along the line of sight tends to cancel the net contribution from $B_w$ (see also Zweibel & McKee 1995). In the following analysis we use a wide range of observations and energy considerations to estimate the magnitudes of $B_S$ and $B_w$ and assess their role in the support of M17 SW.

One useful diagnostic of the importance of the static magnetic field in a cloud comes from equating its static magnetic energy to its gravitational energy. A cloud threaded by a magnetic flux $\Phi_B = \pi R^2 B_S$ can be completely supported
perpendicular to \( B_S \) if its mass does not exceed the magnetic critical mass \( M_\text{crit} \approx 0.13G^{-1/2} \Phi_0 \) (Mouschovias & Spitzer 1976). Inverting this argument, we can determine the critical static magnetic field \( B_{S, \text{crit}} \), which, if present, could fully support the observed mass of the cloud:

\[
B_{S, \text{crit}} \approx 5 \times 10^{-21} N_p \mu G,
\]

where \( N_p \) is the average proton column density of the cloud. If the actual static magnetic field \( B_S > B_{S, \text{crit}} \) (i.e., \( M < M_\text{crit} \)), then the cloud can be completely supported by \( B_S \); it is magnetically subcritical, and further evolution of the cloud perpendicular to the field occurs primarily via ambipolar diffusion. If \( B_S < B_{S, \text{crit}} \) (i.e., \( M > M_\text{crit} \)), then \( B_S \) cannot fully support the cloud, the cloud is magnetically supercritical, and internal motions must supply additional support if the cloud is stable. In this case, further evolution of such a cloud will be controlled in part by processes that create and dissipate internal motions.

The second type of support provided by magnetic fields arises from MHD waves generated in a turbulent velocity field. The requisite turbulent velocity field may be produced by a wide range of sources such as stellar winds, supernovae, and clump-clump collisions. The fluctuating or wave component of the magnetic field \( B_w \) organizes the resulting supersonic (but sub-Alfvénic) motions in the gas so that the effects of highly dissipative shocks are reduced. Theoretical studies suggest that equipartition between a molecular cloud’s kinetic energy and magnetic wave potential energy densities is likely to exist (Zweibel & McKee 1995 and references therein). That is, \( \frac{3}{2} \rho \sigma v_{\text{NT}}^2 = B_w^2/8\pi \), where \( \sigma \text{NT} \) is the nonthermal component of the velocity dispersion. These assumptions lead to the following equation for \( B_w \) (the formal equivalent of eq. [2]):

\[
B_w \approx 0.4 \Delta \sigma v_{\text{NT}} n_p^{1/2} \mu G.
\]

In this equation, \( \Delta \sigma v_{\text{NT}} \) is the nonthermal line width (FWHM) and \( n_p \) is the proton density. Since Zeeman measurements are more likely representative of \( B_\perp \), then \( B_w \) (see above), the relevance of equation (4) to our data is not immediately obvious. However, Zeeman observations of a limited number of other clouds yield \( B_{\text{crit}} \) field values comparable to those predicted by equation (4) (Myers & Goodman 1988a, 1988b, 1991; Bertoldi & McKee 1992; Mouschovias & Psaltis 1995). This coincidence suggests \( B_\perp \approx B_w \), an assumption used in equation (2).

Although the amplitude of \( B_w \) (eq. [4]) may be quite large, it is not clear whether MHD waves last long enough to play a major role in cloud support (see, for example, Gammie & Ostriker 1996; Balsara 1998). The question is by nature complex, since a full treatment requires the use of three-dimensional MHD codes and detailed knowledge of the source. Our goal here is to determine qualitatively if MHD waves can persist on dynamical timescales in M17 SW. There are three timescales that play a key role in answering this question. The first is the free fall time, \( t_{\text{ff}} \). The second is the dissipation timescale, \( t_{\text{dis}} \), of the MHD waves as a function of wavelength \( \lambda \). The third timescale is the crossing time of a MHD disturbance within the cloud, \( t_{x, \text{cross}} \), also a function of \( \lambda \). These timescales place several constraints on the problem. First, \( t_{\text{dis}} \) must be longer than \( t_{\text{ff}} \) in order for MHD waves to persist long enough to be of dynamical importance. This constraint can be relaxed if there are new sources of turbulence in the cloud (i.e., young stellar objects, for example) and the induced MHD waves have \( t_{\text{cross}} < t_{\text{ff}} \). Second, MHD waves with frequencies higher than the ion-neutral collision frequency cannot propagate, so there is a lower limit to the MHD wavelengths. Formally, this criterion is expressed in terms of the parameter \( \Psi = k v_n/2v_\text{A} \), where \( k \) is the wavenumber and \( v_n \) is the collision frequency of neutral molecules with ions (e.g., Nakano 1998). Third, if the propagation speed \( (v_p) \) of a wave is faster than the Alfvén speed \( v_\text{A} \) of the gas, super-Alfvénic shocks are formed that are highly dissipative (McKee & Zweibel 1995). Estimates for \( t_{\text{ff}}, t_{\text{dis}}, \) and \( t_{x, \text{cross}} \) are listed in Table 2 as functions of \( \lambda/2Z \) and the ionization fraction \( x_e \) (2Z is the core extent in the direction of propagation, which we assume is \( \approx 2R \)).

There are several reasons to expect \( x_e \) greater than that produced by cosmic rays alone (\( \sim 1 \times 10^{-7} \)) in the interclump medium of M17 SW. Chief among these is the surprising extent of [C II] 158 \( \mu \)m emission west of the M17 H II region—M17 SW interface. Stutzki et al. (1988) observed [C II] 158 \( \mu \)m emission exceeding that which would be produced by cosmic rays up to 15 pc west of the interface region. This trend is also seen by the presence of CO (7–6) emission 2 pc into the cloud, which must arise from the surfaces of UV illuminated clumps (Fig. 12; see also Meixner et al. 1992; Meixner & Tielens 1993). Myers & Khersonsky (1995) also show that the ionization fraction of the interclump medium in molecular cloud cores with embedded OB stars can be significantly enhanced over that of cosmic rays alone. Because of the concentration of the strongest UV sources to the east and the edge-on geometry of the source, we estimate that \( x_e \) is quite high at the interface ~0.001 and declines to \( \sim 1 \times 10^{-6} \) 5 pc west of the interface region (see also Stutzki et al. 1988; Hollenbach, Takahashi, & Tielens 1991; Myers & Khersonsky 1995).

The minimum \( \lambda/2Z \) implied by requiring \( t_{\text{dis}} > t_{\text{ff}} \) and \( \Psi < 1 \) are listed in Table 3 for several conservative values of the ionization fraction \( x_e \). Two things are obvious from the table: (1) the constraint that \( t_{\text{dis}} > t_{\text{ff}} \) is the dominant factor for the \( \lambda/2Z \) cutoff and (2) a fairly large spectrum of wavelengths can propagate in M17 SW. For example, the most conservative estimate of \( x_e (1 \times 10^{-6}) \) yields a lower limit of

| Parameter | Value |
|-----------|-------|
| \( n_0 \) (average) | \( 6 \times 10^{4} \) cm\(^{-3} \) |
| \( N_e \) | \( 4 \times 10^{22} \) cm\(^{-2} \) |
| Radius | \( 1 \) pc |
| Mass | \( 1.2 \times 10^{4} M_\odot \) |
| Velocity dispersion | \( 2.7 \) km s\(^{-1} \) |
| \( B_{\text{crit}} \) (interclump) | \( 500 \mu G \) |
| \( v_A \) | \( >4.2 \) km s\(^{-1} \) |
| \( f_e \) | 8.3 |
| \( \Phi/\Phi_{\text{crit}} \) | 0.3 |
| \( t_{\text{ff}} \) | 1.1 \times 10^{12} \) s |
| \( t_{\text{dis}} \) | \( 1.65 \times 10^{15} \) s |
| \( \lambda/2Z \) | \( 0.0235(\lambda/2Z)^{-1} \) |

* Goldsmith et al. (1997); from C\(^{18}\)O.
* Nakano (1998); \( f_e = n_0(a/b)^2/2. \)
* Nakano (1998)/s eq. (50).
* Nakano (1998)/s eq. (54).
* Nakano (1998)'s eq. (57).
* \( x_e \) is the ionization fraction, and \( \lambda/2Z \) is the ratio of wavelength to cloud dimension in the direction of propagation.
\( \lambda > 0.15R \), which is only \( \sim 7\% \) of the M17 SW core’s radius. Unfortunately, we cannot place an upper limit on the wavelength (other than 2R), because MHD waves on the size scale of current Zeeman and polarimetry resolutions could easily escape detection because of spatial averaging or field geometry (see above). We also find that the minimum crossing time, \( t_{\text{cross,min}} \), is 1.65 \( \times 10^3 \) s is never less than \( t_{\text{ff}} \). This implies that new MHD disturbances do not have time to propagate across the full extent of the core. However, if the cloud is in quasi-static equilibrium so that the core’s lifetime \( t_{\text{core}} > t_{\text{ff}} \), this criterion may also be met. In addition, \( v_{\text{PH},\text{max}} = 2Z/t_{\text{cross,min}} \) implies \( v_{\text{PH}} \leq 3.8 \text{ km s}^{-1} < v_s > 4.2 \text{ km s}^{-1} \), so super-Alfvenic shocks do not occur. From these considerations it seems likely that a fairly wide range of MHD wavelengths can propagate in M17 SW without dissipation over the free-fall time. Also notice that the range of cutoff wavelengths shown in Table 3 are similar to the size scale of clumps within the M17 SW core (§ 1). This is consistent with the work of Myers (1998), who suggests that stars are formed in “kernels” (our clumps), which are condensations that have been cut-off from MHD waves in the core.

Equations (3) and (4) for \( B_{S,\text{crit}} \) and \( B_w \) combined with previous measurements of M17 SW’s basic properties can now be compared to our H I Zeeman measurements of \( B_{\text{los}} \). Using their C I\(^{18}\)O observations, Goldsmith et al. (1997) estimate that the diameter of the M17 SW core is \( \sim 2 \) pc and that the average hydrogen column density is \( \langle N_H \rangle \approx 2 \times 10^{23} \text{ cm}^{-2} \). From these values we estimate \( \langle N_p \rangle \approx 4 \times 10^{23} \text{ cm}^{-2} \) and \( \langle N_{\text{los}} \rangle \approx 6 \times 10^{20} \text{ cm}^{-3} \) (assumes filling factor of 1). Although \( \Delta v_{\text{FWHM}} \) of optically thin lines, we believe a more accurate estimate for the nonthermal motions of the M17 SW core as a whole comes from the velocity dispersion in the center velocities of its clumps. That is, the clumps represent test particles in the gravitational potential of the cloud. Stutzki & Güsten (1990) identified 179 approximately 0.1 pc C I\(^{18}\)O clumps in M17 SW and provided center velocities for each. The dispersion of these center velocities is \( 2.7 \text{ km s}^{-1} \), equivalent to \( \Delta v_{\text{FWHM}} = 6.3 \text{ km s}^{-1} \). From these parameters and equations (3) and (4), \( B_{S,\text{crit}} \approx 2000 \mu G \), and \( B_w \approx 620 \mu G \). These estimates indicate that (1) unless the total static field \( (B_s) \) is four or more times higher than our maximum values for \( B_{\text{los}} (500 \mu G) \), then M17 SW as a whole is magnetically supercritical and is gravitationally unstable unless there are other forms of support; and (2) the estimate for \( B_w \) is in good agreement with our highest values for \( B_{\text{los}} \). Based on the estimate that \( t_{\text{diss}} \) is longer than \( t_{\text{ff}} \) and that \( B_w \approx 600 \mu G \), it seems likely that MHD waves play an important role in the support and dynamics of M17 SW. Note that these estimates are probably not valid for individual clumps within the core (Bertoldi & McKee 1992).

A more comprehensive perspective on cloud support can be gained from a simplified form of the virial theorem that simultaneously takes into account magnetic effects from \( B_S \) and \( B_w \) but not rotation (see McKee et al. 1993). We note that the inclusion of \( B_w \) in the virial analysis seems to be valid in this case given M17 SW’s high-ionization fraction (in the interclump medium) and the preceding timescale arguments. Assuming the core is neither collapsing or expanding as a whole, the virial theorem can be written

\[
\mathcal{P}_s + |\mathcal{W}| = \mathcal{M}_S + \mathcal{M}_w + 2\mathcal{F},
\]

where \( \mathcal{P}_s \) is the external pressure term, \( \mathcal{W} \) is the gravitational energy, \( \mathcal{M}_S \) is the magnetic energy associated with \( B_S \), \( \mathcal{M}_w \) is the magnetic wave energy produced by \( B_w \), and \( 2\mathcal{F} \) is the energy contribution from internal motions (see McKee et al. 1993 for a more detailed description of these terms). The estimates for each of these terms, given in Table 4, can now be used to estimate the theoretical value of the static magnetic field \( B_S \). Note that we have assumed \( \mathcal{M}_w = \mathcal{F} \) because of the likely equipartition between internal motions and \( B_w \) (see above and § 4.1.2). In calculating \( \mathcal{P}_s \) we have utilized the relation \( P/B = 8.0 \times 10^4 (A/3 \text{ mag})^2 \text{ cm}^{-2} \) (K \( \approx \) Boltzmann’s constant; Nakano 1998) and assumed a 300 \( \text{ cm}^{-3} \) 6.5 pc thick halo for M17 SW (Meixner et al. 1992). We have ignored the external pressure from the H II region in this analysis, because we are concentrating on M17 SW (Figs. 13 a and 13b), which seems to be comprised of unshocked gas (see § 4.1). We also ignore the external magnetic field (see, e.g., McKee et al. 1993; Nakano 1998). Given the virial terms estimated in Table 4 we find \( \mathcal{P}_s /|\mathcal{W}| \approx 0.3, B_S \approx 760 \mu G \), and the mass that can be supported by the static magnetic energy is \( M_M \approx \frac{1}{2} M_{\text{core}} \). Therefore, the predicted static field \( B_S \) using this model is in close agreement with the values of \( B_{\text{los}} (\approx 500 \mu G) \) measured toward M17 SW in our H I Zeeman observation. In this model, internal motions in the core are subvirial, since \( \mathcal{P}_s /|\mathcal{W}| < \frac{1}{2} \), and the cloud is magnetically supercritical. That is, the cloud is supported in part by internal motions, with the remainder of the support coming from \( B_S \). Moreover, the magnitude of \( B_S \) in this model is comparable to \( B_W (620 \mu G) \); eq. [4], so that the magnetic support provided by the static and wave components of the field is comparable. This suggests that \( B_S \approx B_w \) is a good assumption for M17 SW (see above).

Although our estimate for \( B_S \) using this simple virial model is quite close to the highest measured values of \( B_{\text{los}} (\approx 500 \mu G) \), this model must be considered somewhat fortuitous, since estimates of \( B_S \) based on virial analysis are very sensitive to uncertainties in cloud parameters and, of course, \( B_{\text{los}} \) is just one component of the field. Also note that if the magnetic wave energy is assumed to be negligible (\( \mathcal{M}_w = 0 \) in eq. [5]), then the static field must be higher to provide compensating support for the cloud. In such a case, we estimate \( B_S = 1200 \mu G \), more than twice our highest

### Table 3

| Ionization Fraction \( (x) \) | \( \langle 2Z \rangle_{\text{min}} \) from \( t_{\text{los}} \) | \( \langle 2Z \rangle_{\text{min}} \) from \( \Psi < 1 \) |
|----------------|----------------|----------------|
| \( 1 \times 10^{-6} \) | \( 0.075 \) | \( 2.4 \times 10^{-3} \) |
| \( 1 \times 10^{-3} \) | \( 0.023 \) | \( 2.4 \times 10^{-4} \) |
| \( 1 \times 10^{-4} \) | \( 0.0075 \) | \( 2.4 \times 10^{-5} \) |

### Table 4

| Energy Term          | Symbol | Value (ergs) |
|----------------------|--------|--------------|
| Gravity              | \( \mathcal{W} \) | \( 9.57 \times 10^{48} \) |
| External pressure    | \( \mathcal{P}_s \) | \( 4.12 \times 10^{48} \) |
| Kinetic energy       | \( 2\mathcal{F} \) | \( 5.22 \times 10^{48} \) |
| Static magnetic energy | \( \mathcal{M}_S \) | \( 298 \times 10^{44} B_s^2 \) |
| Wave magnetic energy | \( \mathcal{M}_w \) | \( 2.61 \times 10^{44} \) |

* Assumes \( \mathcal{M}_w = \mathcal{F} \).
measured $B_{\text{los}}$. Note that this virial analysis pertains to the M17 SW core as a whole ($R = 1$ pc). In a more detailed analysis of magnetic effects, Nakano (1998) concludes that MHD waves damp too quickly to be of dynamical importance in "cores." However, these cores are much smaller structures, equivalent to the "clumps" in M17 SW ($R \sim 0.1$ pc) described by Stutzki & Güsten (1990). Therefore, the results of Nakano are not relevant to M17 SW as a whole.

One other virial method has commonly been used in the literature to estimate field strengths in self-gravitating clouds (see Myers & Goodman 1988a, 1988b; Mouschovias & Psaltis 1995; Bertoldi & McKee 1992; McKee & Zweibel 1992; McKee et al. 1993). Letting $\Delta f = |\langle \Psi \rangle|$, we obtain the following mass estimate:

$$M = \frac{5}{8 \ln 2} \left[ \frac{\Delta v_{\text{NT}}^2 R}{aG} \right],$$

where $a$ parametrizes the extent to which a magnetic field is needed to support the cloud; i.e., $a < 1$ for clouds in which the internal motions are subvirial. Substituting this estimate for the cloud's mass into equation (4), we obtain

$$B_W = 15a^{-1/2} \left[ \frac{\Delta v_{\text{NT}}^2}{R} \right] \mu G,$$

where $R$ is in pc and $\Delta v_{\text{NT}}$ is in km s$^{-1}$. Goldsmith et al. (1997) estimate that the mass of M17 SW is $M_{\text{core}} = 1.2 \times 10^4 M_\odot$ (including helium) on the basis of their C$^{18}$O maps. Comparing this mass to that computed from equation (6), $M = a^{-1} 8.5 \times 10^3 M_\odot$, we find $a = 0.7$ and $B_W \approx 740 \mu G$. The fact that the field strength predicted by equation (7) is relatively well matched by $B_{\text{los}}$ (500 $\mu G$) may be another indication that $B_W \approx B_3$ (see above).

5. SUMMARY AND CONCLUSIONS

The H i absorption lines toward M17 show complicated profiles with 5–8 distinct velocity components. In general, the highest H i column densities are concentrated toward the H ii region–M17 SW boundary. This effect is particularly noticeable in the velocity range of the 20 km s$^{-1}$ H i component. A lower limit to the maximum H i column density summed across the whole H i velocity range is $N_{\text{H}i}/T_e = 1.0 \times 10^{20}$ cm$^{-2}$. Atomic and molecular emission temperature measurements suggest that $T_e$ lies between 50 and 200 K.

A magnetic field has been detected at the same velocity as M17 SW ($v_{\text{LSR}} \sim 20$ km s$^{-1}$), which peaks steeply toward the M17 H ii region–M17 SW interface to values of $B_{\text{los}} = -450$ $\mu G$. Analysis of this H i component's line width, along with its velocity and spatial coincidence with molecular density tracers along the M17 SW molecular ridge, suggests that it originates in unshocked PDR gas. Comparison of the proton density implied by the observed $B_{\text{los}}$ and the 20 km s$^{-1}$ H i density show that the H i gas is only a ~1%–5% constituent of the gas along the line of sight toward M17. At the same time its distribution along Stutzki et al.'s (1988) strip scan across the H ii region–M17 SW boundary agrees well with that of molecular gas. Therefore, we suggest that the 20 km s$^{-1}$ H i gas either lies in dense, thin shells around the numerous molecular clumps that have been observed in M17 SW or that it is well mixed with fairly dense ($1 \times 10^4$ cm$^{-3}$) interclump molecular gas. In addition, the region of maximum $B_{\text{los}}$ for this component agrees spatially with a minimum in 100 $\mu$ polarization that samples the plane of sky magnetic field.

Another significant $B_{\text{los}}$ was observed in the blended component at 11–17 km s$^{-1}$ with values reaching ~ +550 $\mu G$. The morphology of high $N_{\text{H}_2}$ for this component is quite different from that at 20 km s$^{-1}$, with the greatest concentrations found further east and toward the northern parts of the source. From these components' morphology and line width and from evidence that there is a significant amount of obscuring material on the front side of the M17 H ii region, we suggest that the 11–17 km s$^{-1}$ components originate in shocked gas that is streaming toward us along the line of sight. Estimates of the shock speeds that can be produced by the M17 H ii region agree well with these components' blueshift (2–8 km s$^{-1}$) with respect to the rest velocity of the region. Like the 20 km s$^{-1}$ H i component, the 11–17 km s$^{-1}$ H i gas can only comprise ~1% of the line-of-sight gas, and it may be confined to photodissociated H i shells surrounding molecular clumps close to the H ii regions front side.

Using various virial arguments we have estimated that M17 SW is subvirial ($\langle v \rangle/\langle \Psi \rangle < \frac{1}{2}$) and magnetically supercritical ($M_{\text{core}} > M_\odot$). In our model, about half of M17 SW's total support is provided by its static magnetic field $B_S$ ($\sim 760$ $\mu G$), with the rest of the support arising from internal motions, including support from the wave component of the field $B_W$. The inclusion of $B_W$ in the energy balance of M17 SW is justified, because the relatively high-ionization fraction in the interclump medium should allow a fairly wide spectrum of MHD wavelengths to persist undissipated on dynamical timescales. Estimates of the static ($B_S$) and wave ($B_W$) components of the magnetic field indicate that they are of approximately the same magnitude ($\approx 600$–800 $\mu G$) and agree well with our highest values of $B_{\text{los}}$ ($\approx 500$ $\mu G$).

Subsequent analysis of higher resolution VLA H i Zeeman effect data will give better sensitivity to $B_{\text{los}}$ if the field is tangled and will allow us to better differentiate separate velocity components. In addition, observations of the Zeeman effect in OH may also help untangle the magnetic field data at this interface, since it tends to trace somewhat higher density gas.

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