Shocks and Molecules in Diffuse Interstellar Cloud Pairs

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Abstract

The diffuse interstellar medium (ISM) is dynamic, and its chemistry and evolution are determined by shock fronts as well as photodissociation. Shocks are implied by the supersonic motions and velocity dispersion, often statistically called “turbulence”. We compare models of magnetohydrodynamic (MHD) shocks, with speeds typical of cloud motions through the ISM (3–25 km s\(^{-1}\)) and densities typical of cold neutral gas (\(\sim 10^7\) cm\(^{-3}\)), to archival observations of the H\(^1\) 21 cm line for gas kinematics, far-infrared emission for dust mass, and mid-infrared emission for high-resolution morphology, to identify shock fronts in three high-latitude cloud pairs with masses of order 50 \(M_\odot\). The clouds have “heads” with extended “tails,” and high-resolution images show arcs on the leading edges of the “heads” that could be individual shocks. The H\(^1\) shows higher-velocity gas at the leading edges due to shock-accelerated material. For two cloud pairs, one cloud has an active shock indicated by broad and offset H\(^1\), while the other cloud has already been shocked and is predominantly “CO-dark” H\(_2\). Two-dimensional MHD simulations for shocks parallel to the magnetic field for pairs of clouds show a remarkable similarity to observed cloud features, including merged “tails” due to aligned flow and magnetic field, which leads to lateral confinement downstream. A parallel alignment between magnetic field and gas flow may lead to formation of small molecular clouds.

Unified Astronomy Thesaurus concepts: Diffuse interstellar clouds (380); Diffuse molecular clouds (381); Shocks (2086); H I line emission (690)

1. Introduction

The interstellar medium (ISM) within \(\sim 200\) pc of the Sun is pervaded by diffuse, low-density gas at temperatures of thousands of kelvin (the so-called “warm neutral medium”, or WNM) and denser concentrations of gas at temperatures of order 100 K (the so-called “cold neutral medium”, or CNM); for reviews see Kulkarni & Heiles (1988) and Dickey & Lockman (1990). These phases are often considered to be in pressure balance, and a two-phase solution that can match the approximate average properties of CNM (\(T \sim 80\) K) and WNM (\(T \sim 8000\) K) exists for a narrow range of thermal pressures (Field et al. 1969; Wolfe et al. 2003). But is the ISM really in equilibrium? Evidence suggests the contrary. Static models cannot explain why 48% of the atomic gas is in the “unstable” temperature range between the CNM and WNM, calling into question whether there really are two distinct phases in the first place (Heiles & Troland 2003). The prevalence of diffuse gas in the intermediate temperature range 250–1000 K was confirmed in a large, recent survey where 51% of the lines of sight detected in absorption, amounting to 20% of the total gas mass, comprises an “unstable neutral medium” (UNM) (Murray et al. 2018b).

The ISM is dynamic, being subjected to shock waves from supernovae: with a supernova occurring every \(\sim 50\) yr in the Milky Way (van den Bergh & Tammann 1991), any point in the disk can be expected to be within 100 pc of a supernova every 10 Myr. High-temperature (\(\sim 10^6\) K) gas pervades large volumes of the ISM, forming a “hot ionized medium” (HIM; see McKee & Ostriker 1977), effectively the interior of single and multiple supernova remnants. Even without new supernova shocks, the gas is already so highly agitated that shocks will arise from CNM–WNM and CNM–CNM interactions, because motions of clouds are supersonic. Cloud motions relative to surrounding gas are readily evident from wide-area H\(^1\) surveys (Heiles & Habing 1974), with the most common “low-velocity” clouds being within \(30\) km s\(^{-1}\) of the local standard of rest (LSR), “intermediate-velocity” clouds being up to \(90\) km s\(^{-1}\) (Magnani & Smith 2010), and “high-velocity” clouds at even higher velocities (Wakker & van Woerden 1997). The sound speed is approximately \(1\) km s\(^{-1}\) for the CNM and 10 km s\(^{-1}\) for the WNM. If we focus upon well-defined (smaller than a few parsecs) concentrations of material in the local ISM with column densities \(>10^{20}\) cm\(^{-2}\), their densities are high enough that they will be considered CNM, and typical cloud velocities relative to the local standard of rest are supersonic. Within low-velocity gas, cloud motions through intercloud gas will drive shocks with Mach numbers of 2–20. If an intermediate-velocity cloud interacts with low-velocity gas, shocks with Mach numbers 20–90 will result. And if a high-velocity cloud interacts with low-velocity gas, strong shocks with Mach numbers of 100 and higher will result.

This simple realization means that all interstellar “clouds” will contain shock fronts either at their surface, possibly defining what we consider to be the “edge” of a cloud, or throughout older clouds. This point has not eluded astronomers in the past, and Cox (1979) inferred that most interstellar clouds should contain at least one shock. The average Mach number in the cold, diffuse ISM excited by supernovae is estimated to be \(3.7\) (see Equation (39a) of Heiles & Troland 2005) to \(\sim 2\) (Li et al. 2015). The very local ISM may be involved in an expanding shell from nearby OB stars, which is even detected as interstellar dust moving through the solar system (Frisch et al. 1999). While it is tempting to rely on
static, equilibrium models dominated primarily by photodissociation and radiative cooling, nature is significantly more complicated and requires a wider vision that can also include the “unstable” H I temperatures, the prevalence of “hot” X-ray gas, and supersonic motions. While cold, atomic clouds are readily evident in 21 cm H I surveys, the medium in which they travel is not as readily evident and could be a warm atomic or ionized medium (WNM or CNM, $T \sim 10^4$ K) or hot ionized medium (HIM, $T \sim 10^6$ K).

In the CNM, evidence points toward a significant amount of molecular gas in diffuse clouds that was not known from CO surveys. Our previous work identified a sample of clouds that we now realize are primarily composed of “CO-dark” molecular gas (Reach et al. 2015), a feature of interstellar clouds that had been independently found to be present in the ISM from infrared (Heiles et al. 1988, hereafter HRK) and γ-ray (Grenier et al. 2005) studies. Analyzing H I surveys showed that cold clouds, with median internal velocity dispersion of 3.2 km s$^{-1}$, have total mass 2.5 times the H I mass alone (Kalberla et al. 2020). The CO-dark molecular gas is a common ingredient of galaxies (Leroy et al. 2007), in particular dwarf galaxies (Fahrbrock et al. 2017; Chevance et al. 2020). This additional mass is not optically-thick H I (Lee et al. 2015; Reach et al. 2017b; Murray et al. 2018a).

To understand many of these diverse phenomena, we consider in this paper the possibility of finding individual shock fronts in diffuse clouds. Small-scale structure in the ISM is clearly evident using higher-resolution techniques as they come online. A review of “tiny” scale atomic structure addresses scales of 0.05 pc, which can actually be resolved for nearby clouds, and which have excess pressure (Stanimirović & Zweibel 2018). We concern ourselves here with identifying individual shock fronts as laboratories for detailed study. The statistical description of a medium pervaded by such shocks may be supersonic turbulence, in current astronomical terminology. The shocks set the chemistry, thermodynamics, and kinematics of the gas and are a more apt description of the interstellar medium than static photodissociation regions (Tielens & Hollenbach 1985) where starlight and extinction are the sole determinants of chemistry. The energy density of starlight is 140 times less than the energy density of gas motions for nominal conditions in the cold neutral ISM with density 10$^2$ cm$^{-3}$ and flow velocity 10 km s$^{-1}$, so any mechanism that taps into at least 1% of the kinetic energy density is more powerful than starlight. When turbulence is dissipated in the cold ISM, it dominates chemistry, forming turbulence dissipation regions (Godard et al. 2009). In denser regions, observed supersonic CO line profiles can be explained as intermittent turbulence (Falgarone et al. 2009).

The effects of starlight and shocks are of course always combined, and distinguishing them at an observable level remains challenging. Elitzur & Watson (1980) stated that “unambiguous detection of shocks in the general interstellar medium had eluded investigators.” Significant progress in theoretical modeling has been made in the meantime, with emphasis on understanding the line emission from high-intensity shocks driven by stellar outflows and supernova remnants (Hollenbach & McKee 1989; Draine & McKee 1993; Neufeld et al. 2019). Molecular hydrogen emission has been detected from diffuse clouds, potentially due to shocks (Ingalls et al. 2011). The purpose of this paper is to pinpoint shock fronts within well-defined, diffuse CNM clouds and determine their gross physical properties. We hope to enable further studies of the physical properties of the ISM, both observational and theoretical. We utilize archival data from a large-scale H I survey (McClure-Griffiths et al. 2009) and the Planck far-infrared dust survey (Planck Collaboration et al. 2014a), together with theoretical calculations using the Paris–Durham shock model (Flower & Pineau des Forêts 2003, 2015).

2. Predictions for Interstellar Shocks

2.1. Analytic

To locate shocks in specific, diffuse interstellar clouds, we first need to know some the distinct signatures of such shocks. For a strong shock into diffuse gas, the temperature of the gas behind the shock reaches a maximum of

$$T_{\text{post}} = \frac{3 \mu m_H v_s^2}{16 k}$$

(1)

where $\mu$ is the mean particle mass in the heated gas ($\mu = 1.27$ for atomic gas, with 10% He), $m_H$ is the mass of a hydrogen atom, $k$ is the Boltzmann constant, and $v_s$ is the shock velocity. For shocks at speeds 5–25 km s$^{-1}$, the temperature behind the shock is 690–19,000 K. The gas behind the shock cools in a time

$$t_{\text{cool}} = \frac{k T}{n A},$$

(2)

where $A$ is the cooling rate, for the range of densities and temperatures of shocked CNM clouds. The primary coolants for CNM gas at post-shock temperatures are atomic fine-structure lines ([O I] 63 $\mu$m and [C II] 158 $\mu$m), H recombination (Lyman $\alpha$ and $\beta$) and rovibrational lines of H$_2$. The cooling rate increases with temperature and leads to a cooling time for CNM gas of

$$t_{\text{cool}} \sim 3000 \left(\frac{n}{100 \text{ cm}^{-3}}\right)^{-1} \text{yr.}$$

(3)

The cooling times are shorter than cloud crossing times, so the shock fronts are shorter-lived phenomena than clouds as a whole. The thickness of the layer of shock-heated gas (viewed perpendicular to the plane of the shock) can then be estimated as

$$L_{\text{cool}} = \frac{1}{4} v_s t_{\text{cool}} \sim 0.01 \left(\frac{v_s}{10 \text{ km s}^{-1}}\right) \left(\frac{n}{100 \text{ cm}^{-3}}\right)^{-1} \text{ pc.}$$

(4)

This sets the scale length of shocks to relate to small-scale structure in interstellar clouds.

The dynamical signature of a strong gas-dynamical shock front can be understood as follows. We describe a strong shock moving perpendicular to the line of sight, i.e., with inclination angle $i = 0$. A strong shock has the kinetic energy per particle dominating the thermal energy per particle, $m_H v_s^2 \gg 3kT_i$, where subscript 0 denotes the unshocked ambient gas. Referring to Figure 1 as a pictorial representation, the shock front is at the vertical double-headed arrow. In the frame of the universe, the shock moves into the ambient gas from right to left with velocity $v_s$.

It is sometimes clearer to describe velocities in the frame of the shock, where atomic upstream gas (region 0, depicted in red, just to the left of the shock in Figure 1) flows into the
(stationary) shock from the left, moving toward the right with velocity \( v_s \). Just behind the shock (region 1, just to the right of the shock in Figure 1), the gas is hot (per Equation (1)), making the blue region in Figure 1, and it slows to velocity \( v_s/4 \). The gas remains atomic just behind the shock because of the short timescale. As the gas moves downstream from the shock toward the right, it cools over the distance \( L_{\text{cool}} \) (returning to the color red in Figure 1), gets denser, and slows toward zero velocity. In this cold, dense gas, molecules begin to form, as indicated by the color transitioning from red to green; this defines region 2.

When a magnetic field is present we have magnetohydrodynamic (MHD) shocks instead of gas-dynamical shocks. The properties of MHD shocks are determined by the relative orientations between the shock front, the upstream magnetic field \( B_0 \), and the upstream velocity \( V_0 \); all of these can be different. We restrict our description to strong shocks, of which we distinguish three types: parallel shocks, perpendicular shocks, and oblique socks.

The first two are relatively simple. For a parallel MHD shock, the upstream magnetic field \( B_0 \) is aligned with the shock velocity \( V_0 \), so the field has no dynamical effect: \( B \) does not change across the shock front and the behavior is just like a gas-dynamical shock; a strong shock has \( V_0 \gg V_{\text{sound}} \). For a perpendicular shock, \( B_0 \) and \( V_0 \) are perpendicular so the upstream gas drags the magnetic field lines along with it. A strong shock has \( V_0 \gg V_{\text{ Alfven}} \). Flux freezing makes \( n \propto B_\perp \) along the flow; for a strong shock, both \( n \) and \( B_\perp \) increase by a factor of 4 just across the shock.

The oblique case is general and includes the parallel and perpendicular cases (Section 7.21 of Fitzpatrick 2014). For oblique MHD shocks it is convenient to convert to a frame in which not only is the shock stationary, but also the upstream velocity \( v_0 \) and field \( B_0 \) are parallel; in Figure 1, this is accomplished by adding the appropriate vertical velocity to \( v_s \). In this frame, the parallelism between \( v_0 \) and \( B_0 \) makes the upstream (region 0) look just like the parallel MHD shock described above. Indeed, \( B_1 \) is unchanged across the shock, i.e., \( B_{1,0} = B_{0,0} \). But \( B_{1,0} \) does change across the shock, thus generating a component \( B_{\perp,1} \). This non-intuitive behavior is called a 'switch-on' shock.

For all three cases, the gas radiates thermal energy and becomes denser as it moves downstream from region 1 toward region 2. In this flow, the total post-shock pressure \( P_{\text{tot}} = P_{\text{mag}} + P_{\text{th}} \) stays roughly constant. The thermal pressure \( P_{\text{th}} = 3nkT/2 \), so as the gas cools the density increases with decreasing temperature; flux freezing makes \( B \) increase, too. The magnetic pressure \( P_{\text{mag}} = B^2/8\pi \), so as the temperature drops \( P_{\text{mag}} \propto T^2 \). If the field is strong enough, the magnetic pressure will come to dominate the thermal pressure at some particular post-shock temperature; in practice for the atomic ISM, this does, in fact, occur. Downstream from where this happens, the total pressure is dominated by magnetic pressure and the density \( n \) no longer increases with decreasing temperature. At that point in the flow, \( B_\perp \) has increased while \( B_\parallel \) has remained constant, so downstream from the shock the field lines become rotated toward being perpendicular to the shock normal (i.e., parallel to the plane of the shock) by an amount depending on the density ratio \((n_2/n_1)\).

### 2.2. Computational

For a detailed prediction of the properties of a diffuse cloud shock, we utilized the Paris–Durham shock model (Flower & Pineau des Forêts 2003, 2015; Lesaffre et al. 2013) to calculate the structure and chemistry for C-type shocks of velocity 5–20 km s\(^{-1}\) into gas with density 10–1000 cm\(^{-3}\). The model accounts for gas chemistry and ion–neutral separation in the shocked gas. An important caveat is that these are one-dimensional models, so they do not include the diverse effects of three-dimensional reality. We discuss comparison to two-dimensional MHD simulations in Section 7.2 below.

The initial magnetic field was assumed to have strength \( B = bn_0^{0.5} \mu G \), where \( n_0 \) is the pre-shock density in cm\(^{-3}\), with the field orientation perpendicular to the shock velocity. With \( b = 1 \), for a 100 cm\(^{-3}\) CNM cloud, this scaling yields a magnetic field of 10 \( \mu G \). The actual magnetic field strength for CNM clouds of the size we are studying is not well known. A median magnetic field strength of 6 \( \mu G \) was derived from 21 cm Zeeman surveys and also from synchrotron emission (see review by Heiles et al. 2005). The median field refers to randomly selected lines of sight toward radio sources. Those lines of sight are unlikely to cross the center of CNM clouds, which we show below are highly structured, so the randomly selected lines of sight are likely to sample regions with lower density (and magnetic field) than are sampled by our directed studies of cloud peaks.

Initial conditions of the pre-shock cloud were set for a photodissociation region with the interstellar radiation field (ISRF) at the solar circle (Mathis et al. 1983). Cosmic rays permeate the pre-shock and shocked gas with constant ionization rate \( \zeta = 5 \times 10^{-16} \text{s}^{-1} \); this cosmic-ray rate is about
a factor of 10 higher than used historically, inferred from relatively recent observations of H$_3^+$ (Indriolo & McCall 2012) and OH$^+$ (Bacalla et al. 2019).

Table 1 summarizes the shock models. To measure properties of the shock-heated region, we somewhat arbitrarily defined the cooling layer as where the temperature was 20% higher than the final temperature. The primary coolants in the shock-heated region are listed for each model, with the O I 63 μm line being the primary coolant for much of the explored parameter space, with significant contributions by the [C II] 158 μm line from the slowest, low-density shocks, and contributions by H$_2$ from the faster shocks. The model cooling lengths from our analytic estimate in Equation (4) are within a factor of 2 of the detailed model simulations over the range of density and shock velocity considered here.

The rapid changes in gas properties occur in a transition layer that is ~0.02 pc thick for CNM conditions and a nominal, 10 km s$^{-1}$ shock. Figure 2 shows the abundances versus distance behind the nominal shock. The H chemistry, which is of primary importance for this project, shows the shocked layer primarily atomic, with H$_2$ formation only at the highest column densities where extinction slows photodissociation. The O abundance remains constant throughout the shock, which is important because of its role in cooling the shock-heated gas. The abundances behind the shock reveal certain molecules characteristic of non-equilibrium chemistry, such as CH$^+$ and O$^+$, which are produced in and largely confined to the heated layer just behind the shock front. Many molecular species, such as H$_2$ and H$_2$O, gradually increase in the cooling gas, but they are primarily increasing because the column density and extinction increase. The carbon chemistry is driven primarily by ISRF ionization and has the structure of a photodissociation region. Oxygen remains primarily atomic, with O-bearing molecules and ions more than an order of magnitude lower in abundance. Some molecules, such as OH and CO are produced both in the shock and in the cooling gas.

At each distance behind the shock, and for each gas species, we can define an emissivity as a function of velocity by taking

| $n_0$ (cm$^{-3}$), $T_0$ (K) | $n_{max}$ (cm$^{-3}$) | $T_{max}$ (K) | $N_{max}$ (10$^{20}$ cm$^{-2}$) | $L_{cool}$ (pc) | Coolant |
|-----------------------------|------------------------|----------------|-------------------------------|----------------|---------|
| $n_0 = 10$ cm$^{-3}$, $T_0 = 208$ K | 5 3.3 310 0.08 0.009 C$^+$, O | 5 3.3 310 0.18 0.002 O | 7 4.7 930 0.24 0.002 O | 10 7.1 2500 0.12 0.12 O, C$^+$ | 12 8.7 3800 0.16 0.15 O |
| $n_0 = 100$ cm$^{-3}$, $T_0 = 55$ K | 5 3.2 310 0.18 0.002 O | 7 4.7 930 0.24 0.002 O | 10 7.1 2500 0.12 0.12 O, C$^+$ | 12 8.7 3800 0.16 0.15 O | 15 11 5900 0.34 0.17 O, H$_2$ |
| $n_0 = 1000$ cm$^{-3}$, $T_0 = 42$ K | 5 3.3 310 0.18 0.002 O | 7 4.7 930 0.24 0.002 O | 10 7.1 2500 0.12 0.12 O, C$^+$ | 12 8.7 3800 0.16 0.15 O | 15 11 5960 0.59 0.003 O, H$_2$ |

Figure 2. Abundances behind a shock front of speed 20 km s$^{-1}$ into gas with density 100 cm$^{-3}$, for the case where the magnetic field is perpendicular to the shock velocity. The shock-heated layer is at 0.01 to 0.04 pc, where some species rapidly increase in abundance. Most neutral molecules increase in abundance in the cooler layer behind the shock, primarily due to extinction and self-shielding.
the modeled abundance of the species and spreading it as a Gaussian with thermal dispersion
\[
\sigma(p, z) = \sqrt{\frac{kT(p, z)}{\mu_p m_{\text{H}}}},
\]
where \(p\) is the species (H, H\(_2\), and CH\(^+\) for this figure) and \(z\) is the distance behind the shock. The central velocity for each species at each distance behind the shock is set to neutral gas velocity (H and H\(_2\)) or ion velocity (CH\(^+\)). This procedure yields the velocity distribution for each species,
\[
\frac{dn}{dv}(p, z, v) = \frac{n(z)e^{-(v-v(z)-v_p \cos \theta)^2/2\sigma^2}}{\sqrt{2\pi} \sigma}
\]
where \(\sigma\) is the thermal dispersion as in Equation (5) and \(v_p(z)\) is the velocity at distance \(z\) behind the shock appropriate to each species (neutral for H and H\(_2\) and ionized for CH\(^+\)).

Figure 1 shows the velocity distribution of H\(_1\), H\(_2\), and CH\(^+\) density for a 20 km s\(^{-1}\) shock into gas with initial density 100 cm\(^{-3}\). The relation between the shock velocity projected by inclination to the line of sight, the speed of the shocked and cooled gas, and the cooling layer, as introduced in the analytic section above, are indicated on the figure. The evolution and velocity distribution of the three species are distinct.

1. The abundance of CH\(^+\), chosen for illustration as a shock-only tracer, peaks just behind the shock front then rapidly drops as the gas cools. One signature of a diffuse shock is CH\(^+\) emission in a thin layer and wide velocity dispersion. This signature is worthy of future study and can be used to confirm shocks, once we locate them.

2. The atomic H is predicted to have a wide velocity profile for a line of sight centered on the shock front, with width of order \(V_S\), within a layer of size \(L_{\text{cool}}\), which is approximately 0.03 pc for the model case shown here. The width of the H\(_1\) 21 cm line at the location of the shock front is therefore a practical indicator of the shock velocity. The shocked gas is readily distinguished from the pre-shock gas, which has a narrow linewidth and is centered at zero velocity.

3. Further behind the shock front, if it evolves for long enough and the cloud is large enough, H\(_2\) appears. Other than the molecular ions that appear only in the shock front, the molecular gas tracers are predicted to have a relatively narrow velocity component and to arise approximately 0.1 pc behind the shock front. Because the H\(_2\) is cold, and the first energy level of H\(_2\) is 520 K above the ground state, there is no detectable emission from H\(_2\). A proxy such as a low-J CO transition could detect the cold molecular gas, though quantitative usage of the brightness to determine the amount of molecular gas is problematic given that the line optical depth would be unknown and the diffuse clouds we are studying are unlikely to be virialized.

3. Sample of Interstellar Cloud Pairs

To provide candidate locations for interstellar shocks, we selected isolated, approximately degree-sized regions of enhanced ISM column density. Clouds were identified from far-infrared (100 \(\mu\)m) dust images from IRAS, which provided what was at the time by far the best tracer of the structure of the diffuse interstellar medium (Low et al. 1984). The clouds were clearly visible as peaks in both dust and atomic gas distributions and well separated from the Galactic plane (where confusion along the line of sight becomes significant). The initial sample was selected by inspecting the IRAS 100 \(\mu\)m and Hat Creek 21 cm all-sky surveys (HRK). Of particular interest for our study of shocks, some clouds were in pairs. While any single cloud could have a preferred direction of uncertain origin, pairs of clouds that share morphological features indicating a preferred direction offer a clearer indication of hydrodynamic effects. Pairs have been important in many areas of astronomy, where studies of star clusters allow investigation of stellar evolution (Binney & Merrifield 1998; Krumholz et al. 2019) and star (Luhman 2012) and planet formation (Haisch et al. 2001), because stars in each cluster are at nearly the same distance from the Sun and arguably have similar ages. Key advantages of studying interstellar cloud pairs are that their components are at the same distance, will likely have the same age, and they travel through comparable areas of the Galaxy with comparable speeds.

Distances to interstellar clouds are generally not well known. Assuming that the clouds are within the scale height of the Galactic disk \(H \sim 230\) pc derived from local H\(_1\) or [C\(_II\)] scaled to the solar neighborhood (Langer et al. 2014), clouds at 45\(^\circ\) latitude have distances within 160 pc. To assess the distance quantitatively, we used the three-dimensional dust reddening map developed by Green et al. (2019). The great advances with Gaia, Pan-STARRS, and the Two Micron All Sky Survey (2MASS), which have wide coverage with accurate photometry and parallactic distances, make it possible to measure actual distances for some interstellar features that heretofore had to be considered unknown. When working on the clouds in general, we will assume a distance of 100\(d_{100}\)pc for clouds with no known distance, leaving \(d_{100}\) as a free parameter.

The dust column density used in this project was calculated from the far-infrared opacity at 5\(^\prime\) resolution from the Planck survey (Tauber et al. 2010; Planck Collaboration et al. 2011), specifically the “thermal dust” foreground separation (Planck Collaboration et al. 2014b).

H\(_2\) 21 cm line data are from the Parkes Galactic All-Sky Survey (GASS; McClure-Griffiths et al. 2009). This survey used the 64 m Parkes antenna with its multibeam feed. The survey has angular resolution 15\(^\prime\) and velocity resolution 0.8 km s\(^{-1}\), which are important for measuring systematic gas motions that are signatures of interstellar shocks. We specifically use the GASSIII release (Kalberla & Haud 2015), which has side lobes and stray light corrected.

The mid-infrared surface brightness was taken from the Wide Field Infrared Survey Explorer (WISE) all-sky survey (Wright et al. 2010), specifically the WISE Image Atlas served through the Infrared Science Archive. We also used the unWISE coadds (Meisner & Finkbeiner 2014), which provide the all-sky survey of dust emission from the interstellar medium with the highest angular resolution (15\(^\prime\)). The unWISE images are at 12 \(\mu\)m wavelength and have point sources removed, making them ideal for extended emission studies of interstellar clouds.
4. G228 and G230

4.1. Morphology and Kinematics

In our previous papers (HRK, Reach et al. 1994), the cloud G228 was listed as G228.0-28.6, and G230 was listed as G230.1-28.4. The extinction versus distance from the Gaia–Pan-STARSS–2MASS compendium (Green et al. 2019) had no stars with less than the full extinction of the clouds, while all stars beyond 260 pc are essentially fully extinguished, setting an upper limit of $d_{100} < 2.6$. The clouds therefore lie no more than 120 pc from the Galactic plane, i.e., within one scale height of the atomic ISM.

Figure 3 shows the GASS H I and Planck dust maps containing G228 and G230. From the Planck integrated optical depth map, assuming a gas-to-dust mass ratio of 100 and an optical depth (at 353 GHz) per unit H column density of $9.7 \times 10^{-25}$ cm$^{-2}$, the dust mass of the complex comprising the two clouds is $47 d_{100}^2 M_\odot$. Morphologically, each cloud comprises a “head–tail” structure. The “heads” are G228 and G230, which have masses of $23 d_{100}^2 M_\odot$ and $14 d_{100}^2 M_\odot$, respectively. The volume densities of the cloud heads are both approximately $500 d_{100}^{-1}$ cm$^{-3}$ if the H is atomic, or half that if the H is molecular. These two clouds have radically different H I properties, despite appearing similar in total column density of dust and gas. This situation was noticed in HRK: while G230 is dominated by a very narrow (1 km s$^{-1}$ wide) H I profile, the other cloud G228 has two components: a narrow one, at approximately the same velocity as that of G230, and a broader (11.5 km s$^{-1}$ wide) component at a distinctly different central velocity. Based on the distinct H I profiles, we asserted that the clouds have different recent shock histories. The narrow component was attributed to fully cooled gas, and the broader component to more recent or ongoing shocks, so G230 was shocked and has cooled and condensed into a molecular cloud, while G228 is still being shocked.

The WISE image (Figure 4) shows that G228 contains a network of filaments parallel to an abrupt northern edge. The filaments can be partially discerned in deep optical images of the clouds as well (Stark 1995). We believe that these filaments and the abrupt northern edges of the clouds are low-speed shock fronts, supporting our earlier speculation on the nature of these clouds. There are also arc-like structures defining the “leading” edge of G230, where we take “leading” to mean the opposite direction from their “tails” that are evident in Figures 3 and 4. The apparent shock fronts in the WISE image of G228 are narrow, with the sharpest ones at the leading edge of G228 having width approximately 20$''$ that is not quite resolved at the 15$''$ resolution of the image. This sets an upper limit to the width of the heated region behind the shock, $L_{\text{cool}} < 0.007 d_{100}$ pc. For a shock velocity of 11 km s$^{-1}$, the thin structure is consistent with expectations for an individual shock as long as the pre-shock density was greater than 50 cm$^{-3}$. Given that the present density of the cloud is 10 times higher, it appears likely this condition was met. The H I 21 cm column density at the leading edge of G228 is $4.7 \times 10^{20}$ cm$^{-2}$, averaged within the 15$''$ beam of the telescope. If the line-of-sight depth is greater than the beam size but smaller than the cloud size, then the average H I density is $> 60 d_{100}^{-1}$ cm$^{-3}$. Thus it appears that the narrow filamentary structures at the leading edge of G228 are consistent with individual shock fronts into relatively dense CNM gas.

The shock on the leading edge of G228 appears redder in color than the rest of the cloud in the mid-infrared (Figure 4), indicating the relative prominence of 22 µm emission. Some color variation could be created by different angular resolutions of the images comprising this image, but this effect would cause sharp structures (unresolved at the longer wavelengths) to appear more blue or green, not red. The mid-infrared color of the filaments within the clouds may be related to their containing active shock fronts. Two possible mechanisms could explain the color difference of the apparent shocks. One is shattering of larger grains, leading to an enhancement in the abundance of small grains responsible for 22 µm emission but not enhancing the shorter-wavelength emission. The other mechanism for the red color of the apparent shocks is emission from the shocked gas. The surface brightness of the line emission would be $2 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ to provide the observed brightness. The WISE 22 µm band spans 20–26 µm. The obvious choice is the H$_2$ (2–0) line at 28.2 µm, which has been detected from diffuse clouds and could be potentially attributed to MHD shocks (Ingalls et al. 2011), but this is outside the WISE passband. Other possible lines include [Fe II] at 25.99 µm and [S I] at 25.25 µm; both lines are detected in MHD shocks from outflows (Neufeld et al. 2009).

The GASS, Planck, and WISE surveys shed significant light on the nature and histories of the two clouds. The H I profiles from our earlier paper (HRK) are confirmed, including the assertion that the two velocity components are both associated with the infrared clouds (as opposed to being a widespread, diffuse emission). In fact, the wide component is only associated with G228, and it is somewhat spatially offset from the narrow component. Figure 3 shows that the wide H I component peaks on the “leading” edge of the cloud, if we envision the cloud moving through the ISM with the tenuous tail “trailing” behind it. We interpret the wider component as recently shocked gas. Figure 5 shows a position–velocity slice through G228, with the accelerated gas evident as a wider spectral line, spatially coincident with the leading edge of G228, at a velocity offset from the narrow-line emission. This gas should be tightly associated with the thin ridges in the WISE images, which are likely the shock fronts. At the angular resolution of the H I data, this appears to be the case.

4.2. Atomic and Molecular Content

Comparing the Planck and GASS surveys highlights further the drastic differences between the G228 and G230. Figure 6 shows that G230 has a far higher amount of dust per unit atomic gas than G228. We showed earlier that both G228 and G230 contain CO in their cores, with central velocity and width similar to those of the narrow H I component, and CO core brightness comparable between the two clouds (Reach et al. 1994). The Planck and GASS surveys show that the amount of dust per unit atomic gas is radically different between G228 and G230. If we use the gas column density from the H I 21 cm line and the dust optical depth from far-infrared emission (see Equation (4) of Reach et al. 2015), the atomic gas-to-dust ratio is $\frac{G}{D} = 84$ in the regions surrounding the clouds, $\frac{G}{D} = 55$ in G228, and $\frac{G}{D} = 12$ in G230. If the total gas-to-dust ratio is 84 everywhere, then there is significant non-atomic gas in both clouds. The amount of this “dark” gas per unit atomic gas (Equation (7) of Reach et al. 2015) is $f_{\text{dark}} = 1.5$ in G228 and $f_{\text{dark}} = 7$ in G230. There is no large-scale CO emission from the main bodies of the clouds in the Planck CO survey, which sets a limit $W(\text{CO}) < 7$ K km s$^{-1}$ on widespread CO. But we did detect CO from the cloud cores using ground-based telescopes (Reach et al. 1994); the CO brightness was $W(\text{CO}) = 2.1$ K km s$^{-1}$. Mapping observations showed bright CO, extended over approximately 6$''$ × 6$''$ (Stark 1995). For G228, we can estimate the amount of “dark” gas that is required, in
addition to the HI, to yield a standard gas-to-dust mass ratio: $N_{\text{dark}} = 3 \times 10^{20} \text{ cm}^{-2}$. Combining the inferred dark gas column (assumed to be H$_2$) and CO line integral yields the so-called “X factor”, $X_{\text{CO}} \equiv N(\text{H}_2) / W(\text{CO}) \sim 1 \times 10^{20} \text{ cm}^{-2} / (\text{K km s}^{-1})$ if the dark gas is H$_2$. In fact, the “dark gas” is much more widely distributed than the CO detections, so the actual values of $X_{\text{CO}}$

Figure 3. Comparison of the dust (unWISE) and atomic gas (GASS HI 21 cm line) distributions for the clouds G228 and G230. The dust map is in grayscale (black meaning more dust), and the atomic gas contours are overlaid. The blue contours are integrated over the narrow HI component, showing the bodies of the clouds. The red contours are the 21 cm line integrated over the wider component. The broader emission line located upstream of the head of G228 is labeled as G228wide, and the “vertex” where the tails of the two clouds rejoin is labeled. Contours range from $1-5 \times 10^{20} \text{ cm}^{-2}$. The HI 21 cm spectra toward three positions are shown as insets, with arrows indicating their spatial locations near the peak of the wide-line region, the head of G228, and the head of G230.
range from the value at the core quoted above to values $>10 \times 10^{20} \text{cm}^{-2}/(\text{K} \text{ km s}^{-1})$ in the rest of the cloud. For G230, the bulk of the cloud mass is not atomic; if the excess gas is molecular, then its central column density (at the 16' angular resolution of the H\textsc{i} 21 cm line observations) is $N(\text{H}_2) \approx 7 \times 10^{20} \text{cm}^{-2}$ and the inferred $X_{\text{CO}} \approx 3 \times 10^{20} \text{cm}^{-2}/(\text{K} \text{ km s}^{-1})$, which is reasonably similar to the value found in the Galactic plane (Bolatto et al. 2013). Based on these numbers we find that G228 is mostly atomic, comprising approximately 52% atomic gas, 26% dark molecular gas, and 22% CO-traced molecular gas. On the other hand G230 is predominantly molecular, with 10% atomic gas, 80% dark molecular gas, and 10% CO-traced molecular gas. The dust temperatures in the two clouds (17.4 K in G230 and 18.1 K in G228) and the diffuse medium outside the clouds (20.5 K) are in accord with the trend of molecular content versus temperature seen in the sample of clouds observed with Arecibo (Figure 12 of Reach et al. 2017a).

To search for evidence of grain processing in the shocks at the leading edge of G228, where the wide H\textsc{i} component and narrow apparent shock fronts are present, we carefully measured the brightness of the arc and the overall cloud, relative to the sky immediately adjacent, in WISE bands 3 and 4. We find that the brightness ratio between the two WISE bands is identical within uncertainties for the arc and the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure_4.png}
\caption{WISE portrait of clouds G228 and G230, combining the 3.6 and 4.5 \textmu m (blue), 12 \textmu m (green), and 22 \textmu m (red) images.}
\end{figure}
overall cloud. Therefore, there is either no grain processing or the processing maintains the same color ratio. WISE band 3 measures the abundance of polycyclic aromatic hydrocarbons (PAH), while WISE band 4 measures the abundance of transiently heated very small grains (VSG). Maintaining a constant ratio of PAH/VSG indicates that the smallest particles have the same size distribution in the apparent shock fronts and in the main body of the cloud. The abundance ratio of small grains to big grains, which maintain equilibrium temperatures, is slightly elevated for G228 and G230 compared with other clouds, both for VSG and PAH (Reach et al. 2017b).

5. G229 and G225

5.1. Morphology and Kinematics

In our previous papers (HRK, Reach et al. 2017b), the cloud G225 was listed as G225.6-66.4, and the cloud G229 was listed as G229.0-66.1. The two clouds are peaks within a complex
that comprises the most prominent optical interstellar feature in the Fornax constellation as noted by Paley et al. (1991). The extinction versus distance shows that most stars in this direction are fully extincted by the clouds, setting an upper limit of $d < 250$ pc. The Bayesian analysis of Green et al. (2019) for the lines of sight toward these clouds does show a step function at a common distance $230 \pm 25$ pc, meaning these clouds are $210$ pc below the Galactic midplane, approximately one scale height of the atomic gas. The dust mass of the complex comprising the two clouds is $200 \, M_\odot$. Morphologically, the complex comprises a pair of “head–tail” structures, with the tails merging at a vertex. One “head” is G225, which has a mass of $48 d_{100}^2 \, M_\odot$. The density in G225 is highest, at $1000 \, \text{cm}^{-3}$, while the G229 portion has a density of $70 d_{100}^{-1} \, \text{cm}^{-3}$.

Figure 7 shows the mid-infrared image and H1 21 cm position–velocity diagram. The cloud can be described as two bright “heads” followed by roughly parallel tails. The northern head is G225, which also appears in the IRAS point source catalog as IRAS 02365-2950, while the southern head is IRAS 02356-2959 (Beichman et al. 1988). Like many other $100 \, \mu$m-only sources in the IRAS catalogs, these are not truly compact sources and are peaks of interstellar clouds (Reach et al. 1993); when viewed at higher resolution in Figure 7, they comprise extended structure—in particular, bright, arced filaments extending along the direction connecting to the more tenuous tails. The cloud was described similarly by Odenwald (1988) as “resolved into two nuclei, each having its own sinuous tail extending $\sim 14^\circ$ to the south,” which is even further than shown in Figure 7.

The tails extending from the two “heads” merge into a single tail, with a different angle relative to the heads, at a nexus that corresponds to what we call G229. The high-resolution WISE images show that the extended tail beyond G229 actually has multiple striations with different position angles. The range of angles may relate to an evolution of the relative velocity between the cloud and its local ISM in the past. If the relative speed is $\sim 3$ km s$^{-1}$ (discussed below in Section 7.2), then the evolution in directions was over the past $10^6$ yr.

In the 21 cm spectra, there is no clear “wide” spectral line emission that distinguishes itself from the rest of the gas, as occurs for the other clouds in this paper. There is a gradual trend of velocity, but it is $< 5$ km s$^{-1}$ and extends over the entire length of the cloud. This trend could be nothing more than a projection effect due to the inclined velocity vector with respect to the line of sight, which appears to evolve (from the curved cloud morphology) over the length of the cloud. Therefore, we can only set an upper limit on the shock velocity. If there are shocks, and their “wide” component from the immediate post-shock H1 is blended with the unshocked gas, then the shock velocity is $< 4$ km s$^{-1}$.

5.2. Atomic and Molecular Content

Comparing the dust and gas content of G229 and G225 reveals a very similar trend to that seen in clouds G228 and
G230 in the previous section. Figure 8 shows that the cloud “heads” (including G225) have relatively high dust content. The nexus of their tails (G229) has the highest atomic column density but not the highest overall density, as revealed by the Planck far-infrared data. The dust emissivity, or ratio of dust optical depth (at 353 GHz) to HI 21 cm column density, is $\sigma_{353} = 6.7 \times 10^{-25}$ cm$^2$ K$^{-1}$ s$^{-1}$ for G225 and $1.0 \times 10^{-26}$ cm$^2$ K$^{-1}$ for G229. This makes the “tail” emission similar to normal ISM, while the “heads” have much higher dust content per unit atomic gas. The inferred atomic gas-to-dust ratios are $[\text{G}/\text{D}] = 1.4$ in the “head” and $97$ in the “tail”. Thus the heads are almost entirely molecular (98%) while the tails are atomic.

CO observations support this view. Ground-based observations revealed bright emission with line integrals up to 3 K km s$^{-1}$ toward the cloud “heads”, but no detection from the “tails” to an upper limit of $<0.2$ K km s$^{-1}$. If the total column density (inferred from far-infrared optical depth) of the head is molecular, then $N(H_2) = 8 \times 10^{20}$ cm$^{-2}$, and the ratio of H$_2$ column density to CO line integral is $X = 2.7 \times 10^{22}$ cm$^{-2}$, somewhat higher than that of giant molecular clouds. The CO emission is much more spatially extended than the far-infrared emission, with the detected CO being confined to about 6'. Averaging to 16' resolution of the HI survey, we find that the cloud heads comprise approximately 29% CO-bright molecular gas, 69% CO-dark molecular gas, and 2% atomic gas.

6. G243 and G240

6.1. Morphology and Kinematics

The clouds G243 and G240 were known as G243.2-66.1 and G240.2-65.5, respectively, in HRK. The quality of new observations from WISE and GASS is higher than was available in 1988, allowing a new assessment and potential to identify cloud shocks. Figure 9 shows the filamentary morphology in the WISE image, with the brightest parts of the cloud comprising a set of curved, approximately parallel filaments. The appearance suggests a set of shocks due to the cloud moving toward the NE relative to the rest of the local ISM, or equivalently, a shock wave (e.g., from an old supernova) moving into the cloud from the NE. The mass of the complex comprising the two clouds is $58d_{100}^{-2}$ $M_\odot$, with about $11d_{100}^{-2}$ $M_\odot$ and $14d_{100}^{-2}$ $M_\odot$ in the concentrations of G240 and G243, respectively. The density in the concentrations is approximately $500d_{100}^{-1}$ cm$^{-3}$.

The HI 21 cm spectra in the region of G243 and G240 show a narrow spectral component, with FWHM 3.5 km s$^{-1}$, that pervades the brightest parts of the filamentary cloud, as well as a broader component. Figure 10 shows the locations of the broad and narrow emission line components and their spectra. To remove emission on angular scales larger than the cloud, as well as any residual stray light from far sidelobe response, a background spectrum, derived from the lower left corner of the region shown, was removed from all spectra. The dust clouds comprise a set of filaments, with orientation roughly parallel to the interface between the intermediate- and low-velocity HI gas. The wide component is located just NE of (and overlapping with) G240. The configuration is very similar to that seen for G228. After subtracting a background spectrum, a fit to the HI line for G240-IVC (IVC and LVC denote intermediate- and low-velocity clouds) has FWHM 25 km s$^{-1}$ and centroid $-22$ km s$^{-1}$. Comparing to the theoretical expectations from Section 2, the width of the wide component sets the shock velocity $v_s = 25$ km s$^{-1}$. From Figure 1, the difference between the velocities of the IVC and LVC sets $v_s \sin i = 17$ km s$^{-1}$, so the shock is inclined from the line of sight by 25$^\circ$ (i.e., close to an edge-on view) and is impacting the cloud on its far side (with the shock moving toward us).

6.2. Atomic and Molecular Content

To assess the relationship between dust and gas in these clouds, Figure 11 shows the correlation between the Planck data and HI 21 cm column density. In G243, the dust emission is significantly in excess relative to the H I, and as for the other clouds, the infrared excess is likely tracing H$_2$. The G240 portion of the cloud contains the wide H I component. Comparing to the theoretical expectations for shocks, we interpret G240 as having currently-active shocks fronts, while...
G243 is all post-shock gas where H$_2$ has formed. The cooling region is predicted to be <0.1 pc, much less than the separation between the clouds, so we do not identify G240 and G243 as portions of the same shock front. The time to cross these clouds at the inferred shock velocity is 30,000$d_{100}$ yr, which is comparable to the cloud crossing time. This suggests that the cloud shocks are, in astronomical terms, relatively recent.

The dust-gas correlation in Figure 11 shows that G240, where the present, strong shocks are likely to be occurring, also has the highest H I column density and dust emission, with...
approximately “normal” emissivity based on the grain temperature of 18.5 K (Reach et al. 2017a), suggesting that G240 is largely atomic. The concentration G243 has lower HI column density but higher dust optical depth, leading to an enhanced emissivity and an inferred H2 column density greater than HI. There is no CO emission detected from these clouds from our ground-based observations (though limited observations were made) or in the Planck CO map. This suggests that G243 is 72% CO-dark molecular gas and 28% atomic gas.

### 7. Discussion

#### 7.1. Summary of Cloud Properties

Some of the salient properties of the cloud pairs in this study are summarized in Table 2. We can readily identify some trends in the images and the numerical comparisons of the cloud pairs. First, each cloud pair tends to have one component with a filamentary morphology and a wide H1 21 cm line, while the other component has a more compact morphology and significant molecular gas. The wide H1 components for G228 and G240 appear just upstream of the clouds (Figures 3 and 7) and likely represent the locations of shock fronts. For those clouds, we use the width of the “wide” component to estimate the shock velocity. For G225 and G229, no wide component was evident, meaning an upper limit of ∼4 km s$^{-1}$ consistent with the hydrodynamic models described below. The present, average density $n$(H) was estimated from the dust column density $N$(H) + 2$N$(H2) (assuming gas/dust mass ratio 100) and a cloud depth along the line of sight the same as the geometric mean of its length and width in the images.

The dynamics of the gas are determined by the balance between the specific energies of gravity (pulling the gas toward its center of mass),

$$E_G = \frac{2\pi}{3} GN_{tot}R = 1.0 \times 10^9 \left( \frac{N_{tot}}{10^{21} \text{ cm}^{-2}} \right) \left( \frac{R}{\text{ pc}} \right) \text{ erg g}^{-1},$$

(7)

the flow of the surrounding medium (pushing gas along the direction of the flow),

$$E_T = \frac{1}{2} \nu^2 = 5 \times 10^9 \left( \frac{V}{\text{ km s}^{-1}} \right)^2 \text{ erg g}^{-1},$$

(8)

#### Table 2

| Cloud | H I profile  | Fraction of Mass | $V_\nu$ (km s$^{-1}$) | $n$(H)_{tot} (cm$^{-3}$) | $n/n_0$ | $L_{cool}$ (pc) |
|-------|-------------|------------------|-----------------------|--------------------------|--------|-----------------|
| G228.0-28.6 | wide+narrow | 52% | 26% | 22% | 11 | 600 | 7 | 0.02 |
| G230.1-28.4 | narrow | 10% | 80% | 10% | ~3 | 5000 | 3 | 0.003 |
| G225.6-66.4 | narrow | 98% | 2% | 0 | 25 | 150 | 15 | 0.03 |
| G229.0-66.1 | narrow | 2% | 69% | 29% | 700 | 0.03 |
| G240.2-65.6 | wide+narrow | 90% | 10% | 0 | 25 | 150 | 15 | 0.03 |
| G243.2-66.1 | narrow | 28% | 72% | 0 | 700 | 0.03 |
and magnetic pressure (preventing motion perpendicular to field lines),
\[
\mathcal{E}_B = \frac{B^2}{8\pi\mu m_{\text{H}} n} = 1.8 \times 10^{10} b^2 \text{ erg g}^{-1}. \tag{9}
\]

For the “heads” of the cloud pairs in this study, the total proton column density \(N_{\text{tot}} \sim 10^{21} \text{ cm}^{-2}\), the size \(R \sim d_{100} \text{ pc}\), velocity \(v \sim 3-25 \text{ km s}^{-1}\), and we assume \(b = 1 \mu\text{G} \text{ cm}^{-1.5}\) for the magnetic field scaling. This leads to a proportion
\[
\mathcal{E}_G: \mathcal{E}_T: \mathcal{E}_B = d_{100}^2: 4V_c^2: 12b^2, \tag{10}
\]
where \(V_c\) is in km s\(^{-1}\), which means that the gas flow through the intercloud medium is the dominant factor, followed by magnetic pressure. The low proportion for gravity quantifies that these clouds are “diffuse” in the sense of not self-gravitating. Looking at smaller regions, such as the dense core of G225, where the volume density is much higher than the cloud average, the size is small, so self-gravity remains a minor influence. Magnetic energy is significant and becomes comparable to kinetic energy for the slow shocks in G225 and G229.

The specific energies \(\mathcal{E}_{G.T.B}\) can be directly compared to those derived from the Millennium Survey of 21 cm absorption and emission for random lines of sight through the diffuse ISM (Heiles & Troland 2005, hereafter, HT05), where the energy densities \(E_{T,B}\) were derived. The quantities are simply related by \(E = \mathcal{E}/\rho\) where \(\rho\) is the mass density, so the proportions have the same interpretation. The kinetic specific energy using the turbulent velocity \(V_{\text{turb,1D}} = 1.2 \text{ km s}^{-1}\) from HT05 is \(\mathcal{E}_T = \frac{\sqrt{3}V_{\text{turb,1D}}^2}{2} = 2 \times 10^{10} \text{ erg g}^{-1}\), which is smaller than we estimate here for the three cloud pairs, because we are estimating the flow speed through the intercloud medium, which drives shocks into the cloud, as opposed to the thermal or random motions on small scales within the clouds. For the magnetic specific energy, HT05 used a fixed \(B = 6 \mu\text{G}\), which corresponds to \(\mathcal{E}_B = 6 \times 10^3 n_{30}^{-1} \text{ erg g}^{-1}\). Thus using HT05,
\[
\frac{\mathcal{E}_T}{\mathcal{E}_B} \simeq \left( \frac{n}{30 \text{ cm}^{-3}} \right), \tag{11}
\]
which ranges from 5 to 170 for the densities we estimated using the column density divided by cloud size. On the other hand, from Equation (10), we find the ratio
\[
\frac{\mathcal{E}_T}{\mathcal{E}_B} = \frac{1}{3} \left( \frac{V_c}{b} \right)^2, \tag{12}
\]
which ranges from 3 to 200 for the flow velocities estimated from the H\(\alpha\) 21 cm line widths, assuming \(b = 1\). The local energy densities (or specific energies) are higher using our estimates than those in HT05, because the present project is focused on individual clouds, while the HT05 survey was for random lines of sight that tend to miss the denser regions. Also the physical interpretation of the kinetic energy is somewhat different: it was considered “turbulent” in HT05, while it is considered a shocked flow in this work. Nonetheless, the ratio of kinetic to magnetic energy densities is similar for both approaches, with the ratio of turbulent to magnetic energy density (or equivalently, to within a factor of 2, the plasma \(\beta\)) greater than unity. This indicates that for isolated, well-defined clouds, which have higher mass density than average, gas collisions have a greater influence on gas dynamics than does the magnetic field, while for the lower-density regions sampled by absorption line surveys, magnetic field dominates.

The properties of the shocks due to the flow through the intercloud medium are elucidated by comparing the observed properties of the clouds to the predictions in Section 2. For each cloud, we estimate a compression factor from the shock velocity and Table 1, then divide the present density by that compression factor to infer the pre-shock velocity. Model shocks were calculated for each cloud’s combination of pre-shock density and shock velocity. In Table 2, the length \(L_{\text{cool}}\) gives the model widths of the shock fronts. At 100 pc distance, the shock fronts are predicted to subtend approximately \(1’\) for G228, G230, G240, and G243 (and even less for G225 and G229), so they are not resolved by the H\(\alpha\) or far-infrared observations presented in this paper. We discussed above how the thin filaments at the leading edge of G228 seen in the WISE mid-infrared images may be individual shock fronts, which may be marginally resolved.

The clouds as a whole are much larger than the individual shock fronts for CNM gas. In Figures 4, 7, and 9, multiple filamentary structures are evident, so the clouds may comprise a tangled nest of shock fronts. The larger-scale and smoother emission may be from shocks into the lower-density portions of the same cloud. There is no reason to expect the clouds to be monolithic structures with a uniform density. Instead, the lowest-density portions of the clouds will have larger scale lengths. We assume the shocks are driven by motion of the cloud through the surrounding medium, so the same shock velocities (3–25 km s\(^{-1}\)) derived for the shocks into the denser gas would also apply to the lower-density gas. This situation is different from a supernova blast wave (see Reach et al. 2019), where the same pressure is impacting clouds. A shock into a more tenuous part of the cloud with density 5 cm\(^{-3}\) would have a heated layer with thickness of order 1 pc (per Equation (4)), which is the size of the entire cloud and its extended tail. This is consistent with the dynamics being dominated by gas collisions (shocks) for the main body of the cloud, while the tails would be dominated by magnetic fields (plasma \(\beta\) less than 1).

### 7.2. Hydrodynamics and Magnetic Field

Two-dimensional simulations by Altzas et al. (2014) are remarkably similar to the clouds in our sample. The flow of gas was modeled for cloud pairs with varying configurations and orientation of magnetic field relative to flow velocity. The initial conditions had two clouds of radius \(R\) that were separated, in the distance perpendicular to the shock velocity, by 0–4 \(R\), and offset, in the direction of the shock velocity, by 0–8 \(R\). The magnetic field orientation was simulated in the directions parallel, perpendicular, and skewed with respect to the shock velocity. For one-dimensional models, such as discussed in Section 2, the component of the magnetic field parallel to the shock velocity is usually ignored, because it has no effect on the relative ion–neutral dynamics. However, in two dimensions, the effect of the parallel component of the magnetic field becomes evident.

In the simulations of offset cloud pairs, the downstream clouds have significantly different morphology, due to lateral confinement of the gas that reaches the downstream cloud. A magnetic “flux rope” forms behind each cloud, where the magnetic field is focused. In the simulations of separated...
clouds, each cloud has an individual tail, approximately parallel to the other’s. A particularly interesting situation, relevant to the clouds in our sample, is for shock velocity parallel to magnetic field and for cloud separation $2R$: the tails from the clouds merge where the plasma $\beta$ is low in the converging flow (see Mac Low et al. 1994, for the explanation).

Figure 12 shows the simulation by Alúzas et al. (2014) for separation $2R$ and offset $8R$, with magnetic field parallel to shock velocity. Note the merged tails, which are similar to those observed in the cloud pairs G225+G229 and G228+G230. For G225+G229, based upon the lack of H I accelerated to more than $5\text{ km s}^{-1}$ and the remarkable similarity of the MHD simulation with the observations, we assign the shock properties based upon the MHD simulation input, which was a sonic Mach number of 3. If the clouds had CNM temperatures $\sim100\text{ K}$, then the shock velocity is $\sim3\text{ km s}^{-1}$. Inspecting the unWISE and Planck images, the tails are not straight, but instead have a significant twist. This effect is also seen in simulations where the magnetic field is skewed with respect to the shock velocity (Figure 5 of Alúzas et al. 2014).

The cloud pair G243+G240 has some similarity to the MHD simulation with zero lateral separation but $8R$ offset between the clouds (Figure 2(e) of Alúzas et al. 2014). In this case the magnetic flux rope from the upstream cloud falls onto the downstream cloud, which is more compressed. The large H I line widths indicate shock velocities much higher than the MHD simulations, but the general principle of the downstream cloud being more compressed may still apply. This extra compression may contribute to making the downstream cloud (G243) molecular, as evidenced by its elevated dust column density per unit H I column density (red points in Figure 11 of this paper).

The MHD simulations explain what had been a puzzling morphology for high-latitude clouds. Whereas one-dimensional thinking led us to expect the downstream gas from each cloud...
would evolve independently, in fact the parallel component of the magnetic field has a significant effect on the flow, leading to merged tails behind cloud pairs. The simulations also give some insight into the potential age of the merged tails behind cloud pairs. The simulations also show that two-dimensional simulations, in which the clouds are restricted to two dimensions, are unlikely to advance our understanding of the longevity of clouds and their small-scale structure.

7.3. Implications for Formation of Diffuse Molecular Clouds

The observations of cloud geometry and kinematics, in comparison to the MHD simulations, indicate clouds with field parallel to shock velocity. Why do we tend to see this orientation? The answer may lie as much in the formation of the clouds as in their evolution. Hennebelle & Péralt (2000) showed that cold (CNM) clouds condense out of a warm medium (WNM) under conditions that lead to alignment between the magnetic field and the flow. For the “transverse” case where field is perpendicular to flow, the magnetic field becomes compressed and resists condensation, so that a CNM cloud does not form. In contrast, for the case where field is more nearly parallel to flow, the magnetic tension generates transverse velocities that “unbend” the field, leading to condensation of a CNM cloud. The field and flow alignment need not be precise; condensation occurs for alignment within 20°.

Hennebelle & Péralt (2000) further divide the parallel case into a weak-field case, where the magnetic field becomes aligned with the flow, and a strong-field case, where the flow becomes aligned with the field; in either of these cases, the result is toward alignment between field and flow. The weak-field case applies when

$$B^2 < \mu m_wn_v^2$$

(13)

where $n_w$ is the WNM density and $v$ is the colliding flow speed. If we use the empirically observed scaling of magnetic field strength with density for interstellar clouds (extrapolating from larger clouds to the 100 $M_\odot$ clouds considered in this study), $B = bh^{1/2}$, with $b \approx 1$ for $B$ in $\mu G$ and $n$ in $cm^{-3}$, then the weak-field condition becomes only a function of the flow speed

$$v > 7h^{0.5} \text{ km s}^{-1}.$$  

(14)

For the shock properties summarized in Table 2, the strong-field case appples to the G225+G229 cloud pair, which may explain why Figure 12 shows such a strong resemblance to the parallel, magnetic-field-dominated models by Altúzas et al. (2014). The G285+G230 cloud pair is in the weak–strong transition. The G240+G243 cloud pair is in the weak-field case; indeed the Mach number is much higher for these clouds than the theoretical calculations.

We showed that the CNM clouds have evidence of shocks and of a high fraction of H$_2$, both for the cloud pairs in this paper and for a more systematically selected set of clouds (Reach et al. 2017b). Numerical simulations by Clark et al. (2019) showed that Mach $\geq 2$ collisions of $n_0 = 10 \text{ cm}^{-3}$ atomic clouds result in efficient conversion of initially atomic gas to 50% H$_2$. The initial conditions used by Clark et al. (2019) of two identical clouds colliding head-on are not the same as what we envision from the appearance of the shocked cloud pairs presented in this paper, where the clouds appear more dense and are interacting with (or condensed from) a lower-density intercloud medium. Nonetheless the physical properties of the shocked clouds are relevant, and the results are in general accord with the observations presented in this paper. The shocked clouds appear to have a large fraction of H$_2$ that is “CO-dark” (see Figures 6, 8, and 11).
8. Conclusions

Shocks into diffuse clouds should be common, based on their wide range of velocities through their local intercloud medium. Tracers of shocks are observed via absorption lines by transient species that sometimes require endothermic reactions to form (like CH\textsuperscript{+}). Absorption lines sample random pencil beams through the ISM and do not readily map to individual cloud structures. Taking a different approach, we utilized wide-area surveys of H\textsc{i} 21 cm and dust far-infrared emission to identify pairs of shocked clouds. From one-dimensional shock models, we showed that the primary signature of individual shocks from those data would be dynamical, from the width of 21 cm lines and their configuration compared to morphology and inferred shock location and direction.

In all three cloud pairs, there was morphology where a leading edge of the cloud (i.e., the part directly facing the incoming gas, in the rest frame of the cloud) was relatively sharply defined, with “heads” of size \(\sim 0.5\) pc. One potential feature of cloud pairs is that they may be interacting with each other, although for our cloud sample this does not appear to be the case. The head/tail morphology is roughly parallel for both components in each cloud pair. The high-resolution WISE images show intricate, filamentary morphology; each filament likely is either an active shock front or was so recently. The cloud heads are largely molecular, even where no CO was detected, with ‘CO-dark’ molecular gas comprising up to 80\% of the mass. All three cloud pairs have diffuse “tails” of atomic gas that extend for 1–4 pc behind them.

The shocks in the three cloud pairs in this study range from a strong shock with Mach number \(\sim 25\) for G240+G243 to a moderately strong shock with Mach number \(\sim 11\) for G228+G230 to a weak shock with Mach number \(\sim 3\) for G225+G229. The slower shocks are C-type and were modeled with the Paris–Durham shock code, which provides a good explanation of the H\textsc{i} 21 cm line shapes.

The cloud pairs we described should be considered “normal” diffuse interstellar clouds, despite the range of shock velocities. The present shocks, of which we are detecting direct evidence, are likely not the first shock any given cloud has experienced. This explains why the dust/gas ratio and dust properties (inferred from temperature of big grains or very small grain abundance) are similar for most of the diffuse interstellar medium. Essentially, all of the diffuse interstellar medium has experienced shocks within the range of velocities identified in this study, and this shock history is an essential part of understanding the properties of interstellar material.

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