NON-MAXWELLIAN PROTON VELOCITY DISTRIBUTIONS IN NONRADIATIVE SHOCKS

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ABSTRACT

The Balmer line profiles of nonradiative supernova remnant shocks provide the means to measure the postshock proton velocity distribution. While most analyses assume a Maxwellian velocity distribution, this is unlikely to be correct. In particular, neutral atoms that pass through the shock and become ionized downstream form a nonthermal distribution similar to that of pickup ions in the solar wind. We predict the H\textsc{o} line profiles from the combination of pickup protons and the ordinary shocked protons, and we consider the extent to which this distribution could affect the shock parameters derived from H\textsc{o} profiles. The Maxwellian assumption could lead to an underestimate of shock speed by up to about 15\%. The isotropization of the pickup ion population generates wave energy, and we find that for the most favorable parameters this energy could significantly heat the thermal particles. Sufficiently accurate profiles could constrain the strength and direction of the magnetic field in the shocked plasma, and we discuss the distortions from a Gaussian profile to be expected in Tycho’s supernova remnant.

Subject headings: ISM: lines and bands — line: profiles — shock waves — supernova remnants — turbulence

1. INTRODUCTION

Fast interstellar shock waves that encounter partially neutral gas are observable as filaments of pure Balmer line emission if they are young compared to their radiative cooling times (Chevalier & Raymond 1978; Raymond 1991; Ghavamian et al. 2001). The Balmer lines are produced in the thin layer just behind the shock where hydrogen atoms are excited and ionized, and this layer is thin enough that Coulomb collisions cannot bring different particle species into thermal equilibrium. Hence the Balmer lines can be used to probe the physical processes in collisionless shocks.

The Balmer lines have two component line profiles. The broad component arises from neutral H atoms created by charge transfer with postshock protons, and its velocity width is comparable to the downstream proton thermal velocity. The narrow component comes from neutrals that have passed through the shock, but that have not been ionized by charge transfer. Therefore, its velocity width corresponds to the temperature of the preshock gas. The intensity ratio of the broad and narrow components depends on electron and proton temperatures, $T_e$ and $T_p$, so that it can serve as a diagnostic for $T_e/T_p$ immediately behind the shock. This is an important quantity for interpreting X-ray spectra of supernova remnants (SNRs) and for understanding collisionless shocks. In a few cases it has been possible to measure the widths of UV lines of other elements, and therefore the kinetic temperatures, $T_e$, of other ions (Raymond et al. 1995, 2003; Laming et al. 1996; Korreck et al. 2007). The overall result is that the plasma behind relatively slow shocks ($\sim 300 \text{ km s}^{-1}$) is close to thermal equilibrium, while shocks faster than about 1000 km s$^{-1}$ are far from equilibrium, with $T_e/T_p < 0.1$ and $T_e/T_p \sim m_i/m_p$ (Rakowski 2005; Ghavamian et al. 2007). Other important applications of Balmer line diagnostics for collisionless shocks are estimates of shock speed, which can be combined with proper motions to find SNR distances (Winkler et al. 2003), and inferences of cosmic-ray diffusion coefficients from the properties of shock precursors (Smith et al. 1994; Hester et al. 1994; Lee et al. 2007).

All of the current models used to interpret the Balmer line profiles assume that the postshock proton velocity distribution is Maxwellian (Chevalier et al. 1980; Lim & Raga 1996; Laming et al. 1996), although there is no solid justification for that assumption. Coulomb collisions are not able to bring the protons to a Maxwellian rapidly enough, and it is not clear what sort of distribution would be produced by plasma turbulence. Heng & McCray (2007) have recently drawn attention to the importance of sequential charge transfer events in determining the profile of the broad component at shock speeds above about 2000 km s$^{-1}$, where the charge transfer cross section changes rapidly with energy, and this affects some of the diagnostics. Heng et al. (2007) have extended the model effort to a fuller treatment of the hydrodynamics than is usually employed, but they keep the assumption that the proton distribution is Maxwellian.

Ion velocity distributions directly measured in the solar wind are essentially never Maxwellian in the vicinity of shocks. Ion distributions typically have power-law tails or strong anisotropies, with beam components upstream and highly perpendicular enhancements downstream (Sckopke et al. 1983, 1993; Gosling & Robson 1985; Thomsen 1985; Kucharek et al. 2004). The Balmer line profiles of nonradiative shocks provide a unique opportunity to search for non-Maxwellian velocity distributions in astrophysical plasmas.

In this paper we keep the assumption that protons that pass through the shock have a Maxwellian distribution at the temperature given by the Rankine-Hugoniot jump conditions (Draine & McKee 1993), but we add the manifestly non-Maxwellian distribution of protons that pass through the shock as neutrals and become ionized. We consider the potentially observable effects on
the Balmer line profiles including line widths and centroid shifts and how they might affect shock parameters derived from Hα profiles. We also discuss the implications of magnetic field strength and direction and of plasma turbulence on the profiles and the possibility that observed profiles could constrain the field parameters. We briefly consider the implications of non-Maxwellian distributions for the heating of electrons and minor ions.

2. PICKUP IONS

Neutral particles that are ionized in the postshock flow are very much like the pickup ions (PUIs) measured by spacecraft in the solar wind (Moebius et al. 1985; Gloeckler et al. 1993; Isenberg 1995). When neutral atoms slowly flow into the interplanetary medium, they can be ionized by photons from the Sun, by charge transfer with solar wind ions, or by collisions with electrons. At that point, the new ions are streaming with respect to the solar wind plasma at the solar wind speed, $V_{SW}$, which is much larger than the local Alfvén speed, $V_A$. These ions are immediately swept up by the magnetic field in the solar wind. Their velocity component perpendicular to the local magnetic field becomes a gyrovelocity around the field, which, in combination with the instantaneous parallel component, initially forms a monoenergetic ring-beam in velocity space. This ring-beam is unstable, and the particles rapidly scatter toward isotropy by interacting with ambient or self-generated waves, resulting in a velocity-space shell (Sagdeev et al. 1986; Lee & Ip 1987; Isenberg 2005; Bogdan et al. 1991).

In the solar wind, pickup protons are distinguished by their unusual velocity distributions, but heavier pickup ions can also be recognized by their single-ionization states, such as He+ or O+. These ions are immediately swept up by the magnetic field in the solar wind. Their velocity component perpendicular to the local magnetic field becomes a gyrovelocity around the field, which, in combination with the instantaneous parallel component, initially forms a monoenergetic ring-beam in velocity space. This ring-beam is unstable, and the particles rapidly scatter toward isotropy by interacting with ambient or self-generated waves, resulting in a velocity-space shell (Sagdeev et al. 1986; Lee & Ip 1987; Isenberg 2005; Bogdan et al. 1991).

3. CONSEQUENCES FOR SNR SHOCKS

Consider a planar shock in which the downstream magnetic field makes an angle $\theta$ with the shock normal. Since the field component perpendicular to the flow is compressed by the shock, $\theta$ is typically 60°–85°, although of course pure parallel and pure perpendicular shocks maintain their field directions. For a strong shock with a compression ratio of 4, a neutral passing through the shock moves at $\frac{3}{4} V_s$ relative to the postshock plasma. These monoenergetic particles form an unstable ring distribution in velocity space. They can emit plasma waves and interact with these waves to scatter into a more isotropic distribution. Generally, the dominant isotropization process is pitch-angle scattering through the cyclotron resonant interaction with parallel-propagating ion-cyclotron and fast-mode waves (Wu & Davidson 1972; Winske et al. 1985; Lee & Ip 1987; see also Zank 1999; Szegő et al. 2000).

The ring-beam distribution may also be subject to other plasma instabilities, depending on the relative density and downstream conditions. In principle, a downstream magnetic field nearly parallel to the flow can result in bump-on-tail (Gary 1978) or firehose-like instabilities (Winske et al. 1985; Sagdeev et al. 1986). The saturation of the Landau bump-on-tail instability leaves a highly anisotropic beam which still scatters in pitch angle through the cyclotron resonance. The firehose instability could disrupt the beam, but requires both a high density of pickup ions relative to the background plasma and an ionization time-scale much shorter than the timescale for cyclotron resonant pitch-angle scattering. If the downstream magnetic field is nearly perpendicular to the flow, a mirror-mode instability can be excited (Winske & Quest 1988; McKean et al. 1995), but this instability saturates at a much lower level than the resonant ion-cyclotron instability (Yoon 1992), and so may be neglected. In this paper we take the ring-beam of newly ionized protons to quickly stabilize through cyclotron-resonant pitch-angle scattering. In particular, we assume the rapid formation of a bisphecal distribution.

3.1. Bisphecal Distribution

Under most conditions, a given energetic proton is cyclotron-resonant with two parallel-propagating electromagnetic modes. If the proton parallel speed is much faster than the Alfvén speed, $V_A$, both of these waves will be Alfvén waves—one propagating along the field in the same direction as the proton and the other in the opposite direction. Resonant scattering away from the ring-beam will result in the amplification of one of these modes and the damping of the other. Which mode is unstable depends on the position of the ring-beam in velocity space, as determined by the angle of the local magnetic field to the plasma flow direction. The resonant interaction with either wave yields a diffusion which conserves the proton energy in the frame of the wave phase speed, scattering the particles along a sphere in velocity space centered on one of the points $v_{i\parallel} = \pm V_A$, as shown in Figure 1. A useful analytical result is obtained in the case where the damped mode can be neglected and the scattering at each point in velocity space is only due to interactions with the unstable mode. In this case, a steady ring-beam will be scattered to a bisphecal distribution: a uniformly populated shell formed by the two spherical caps which meet at the position of the original ring-beam (Galeev & Sagdeev 1988; Williams & Zank 1994).

Many of the basic properties of this distribution may be obtained geometrically. If the ring-beam of the newly ionized protons is located at $(V_{i\parallel}, V_{i\perp})$ as given by equations (1) and (2), the radii of the two spherical caps are $r_{\pm} = V_{i\perp}^2 + (V_{i\parallel} \pm V_A)^2$. The area of each cap in velocity space is $\pi a_{\pm} = 2 \pi v_{i\parallel} (v_{i\parallel} \pm V_A - V_A)$. Since the particles are distributed uniformly over these areas, the net streaming speed of the bisphecal shell is

$$v_{bulk} = \frac{1}{a_T} \left[ V_A (a_+ - a-) + \pi V_A^2 (v_- - v_+) \right],$$

where the total shell area $a_T = a_+ + a_-$. Clearly, the case of flow perpendicular to the magnetic field, $V_{i\parallel} = 0$, gives $v_+ = v_-$ and $v_{bulk} = 0$. Similarly, for parallel flow faster than the Alfvén
speed, the distribution reduces to a single sphere of radius \( V_A \), and the bulk speed is slowed to \( v_{\text{bulk}} = V_A \). In general, the streaming speed of the bispherical distribution is bounded by \( V_A / C_6 \). Figure 2 shows this streaming speed as a function of magnetic field angle \( \theta \) for several values of the downstream field strength, taking a shock speed of 2000 km s\(^{-1}\) and an upstream proton density of 1 cm\(^{-3}\).

These simple properties may be modified for realistic conditions. For instance, dispersion of the resonant waves will systematically shift their phase speed, and so distort the shape of the shell away from a sphere (Isenberg & Lee 1996). This distortion can be significant if the speed difference between the neutrals and the downstream plasma is comparable to \( V_A \). In addition, an efficient turbulent cascade could maintain the stable wave mode intensity despite the damping by the pickup protons. In this case, the multiple wave-particle interactions with both stable and unstable waves can yield a much different distribution, and even result in particle acceleration through the second-order Fermi mechanism (Isenberg et al. 2003; Isenberg 2005). However, the bispherical expressions provide a reasonable first approximation to the pickup proton distribution expected downstream of a strong supernova shock. In this initial study, we retain the bispherical assumptions, and address these simplifications in the discussion section.

### 3.2. Total Proton Distribution

At any point in the downstream plasma the velocity distribution is the sum of the distributions of the shocked protons and the protons formed by ionization or charge transfer in the downstream gas. If the preshock neutral fraction is small, the distribution is dominated by the shocked protons, and it will be difficult to detect the effects of the pickup protons. These effects will be much easier to see in the shocks of Tycho’s SNR, where the neutral fraction is around 0.85 (Ghavamian et al. 2000), than in SN 1006, where it is around 0.1 (Ghavamian et al. 2002). Figure 3 shows a simple model of a shock propagating at 2000 km s\(^{-1}\) into a medium with \( n_H = n_p = 0.5 \text{ cm}^{-3} \), roughly similar to the values expected for Tycho’s SNR. The proton density just behind the shock is the density of thermal protons, so the increase downstream represents the addition of pickup protons. The neutrals immediately behind the shock make up the slow or narrow component. Their density drops as charge transfer converts them to pickup protons and replaces them with fast or broad-component neutrals. Eventually, collisional ionization removes all neutrals, leaving a fully ionized plasma far downstream. The rate coefficients for charge transfer and ionization by electrons and protons were adopted from Laming et al. (1996). Note that this plot assumes that the pickup protons move with the same bulk speed as the background plasma. This will be strictly true only for a perpendicular shock, since the scattered shell of pickup ions will generally retain some streaming motion with respect to the thermal plasma if the field has a component along the flow.

Figure 4 shows the thermal proton and pickup ion distributions for one choice of the parameters. For the modest Alfvén
speeds expected behind SNR shocks, the PUI distribution is not far from spherical. Thus the total velocity distribution shows a peak with a sharp cutoff plus high-velocity wings from the thermal distribution.

The broad components of the Balmer line profiles will reflect the proton distributions, although they are weighted by the charge transfer cross section. Figure 5 shows the proton velocity distribution profiles in the direction parallel to the shock front obtained by adding the background plasma distribution to the PUI distribution. We have chosen this direction because strong limb brightening is required to make the H$\alpha$ emission from a nonradiative shock bright enough that a high S/N profile can be obtained. The projection is obtained by multiplying the velocity along the magnetic field direction by $\sin\theta$. If the observer is not in the plane containing the preshock and postshock magnetic field, the centroid shift will be reduced. In this paper we do not compute Balmer line profiles, since they depend on specific shock parameters. Such calculations will be needed for the interpretation of observations, but for shocks below roughly 2000 km s$^{-1}$ the variation of charge transfer cross section with velocity is weak enough that the H$\alpha$ profile should closely resemble the proton velocity distribution (see Heng & McCray 2007). It should be kept in mind, however, that the broad component of H$\alpha$ is emitted from a region of varying pickup ion fraction, with values near zero near the shock and approaching the preshock neutral fraction far downstream. Roughly speaking, the H$\alpha$ profile will correspond

![Graph](image)

**Fig. 4.**—Proton velocity distribution for an angle $\theta = 70^\circ$ between the field and the shock normal, an Alfvén speed $V_A = 100$ km s$^{-1}$, and a pickup ion density of 0.25 the total density. The lower dashed line shows the bispherical distribution, the upper dashed line shows the thermal proton distribution, and the solid line shows the total.

![Graph](image)

**Fig. 5.**—Velocity distributions for various combinations of parameters. (a) Ratios of pickup ions to thermal protons ranging from 0.05 (outermost curve) to 0.65. (b) Angles between the field and the shock normal of 45$^\circ$ (outermost curve) and 75$^\circ$. (c) Alfvén speeds of 0.05 $V_A$ (outermost curve) and 0.20 $V_A$. (d) The velocity distribution for a distribution of angles assuming isotropic turbulence upstream and compression of $B_0$ by a factor of 4.
to a pickup ion fraction of about half the preshock neutral fraction.

It is apparent from Figure 5 that the departure from a Maxwellian ought to be detectable with sufficiently high S/N data. The difficulty is that the narrow component, whose intensity is generally dominant, obscures the center of the broad-component profile. The usual procedure of fitting the sum of two Gaussians to the total profile provides adequate degrees of freedom to absorb modest departures from the assumed Gaussians, especially if the far wings of the profile and the background level are poorly defined. For very fast shocks, the drop-off in charge transfer cross section with velocity may suppress the high-velocity tail in any case.

As an estimate of the error that could be made by assuming a Maxwellian proton distribution and using the resulting broad line width to derive a shock speed, we fit the profiles in Figure 5 with single Gaussians and compared those widths to the widths of a pure Gaussian at the temperature expected from shock speed. We find that the Gaussian widths estimated from the Figure 5 distributions are as much as 14% narrower than those predicted for a pure thermal distribution of protons, so the shock speed could be underestimated by 14%. This is the extreme case, however, and underestimates about half that large would be typical. These underestimates would be partly countered if the pickup process provides additional heating to the plasma.

3.3. Plasma Heating

Another possible consequence of the pickup process is plasma heating by the waves generated in the isotropization of the initial ring-beam of newly ionized protons. The energy lost by the protons in scattering from the ring-beam to the final nearly isotropic shell is transferred to the resonant waves. These waves in turn may heat the plasma, either directly or through a turbulent cascade to dissipative modes. In the simple bispherical picture of § 3.1, the energy available to the waves is given by

$$E_w = E_o - E_{BD+} - E_{BD-},$$

where $E_o = mn(V_i^2 + V_A^2)/2$ is the energy in the initial ring-beam and the energy in the bispherical distribution is

$$E_{BD+} = \frac{mn\pi v^2}{d_T} \left[ \frac{V}{V_A} (V || V_A) \pm \left( V_A^2 + v^2_\perp \right) + (v^2_\perp - V_A^2) \right].$$

Figure 6 shows the ratio of the total bispherical energy, $E_{BD} = E_{BD+} + E_{BD-}$ to the initial energy for various combinations of the Alfvén speed and the downstream magnetic field angle. The wave energy in equation (4) is essentially a maximum estimate, since the bispherical distribution has a lower energy than the distributions obtained by including dispersive effects or the replenishment of the stable wave modes (Isenberg & Lee 1996; Isenberg 2005).

The form of the plasma heating which results from the pickup proton generated waves is an active area of research in the solar wind. A phenomenological model which assumes that these waves feed a turbulent cascade which dissipates by heating the thermal ions has been shown to reproduce the observed proton temperatures in the outer heliosphere reasonably well (Smith et al. 2001, 2006; Isenberg et al. 2003; Isenberg 2005). This heating can be important when the upstream neutral fraction is large, and it may therefore affect the estimates of the shock speed from the observed Balmer line width.

3.4. Electron Heating

Electron heating is observed to be very inefficient in fast shocks, so the observed electron temperatures could provide a strong constraint on the wave energy even if only a modest fraction of the wave energy is transferred to the electrons. Observations of young SNRs show that $T_e/T_i$ is less than 0.1 in shocks faster than about 1500 km s$^{-1}$ (Rakowski 2005). Ghavamian et al. (2007) propose that cosmic rays diffusing ahead of a fast shock produce lower hybrid waves which then heat the electrons to a temperature of about 3 keV, and this can reproduce the observed variation of $T_e/T_i$ with shock speed.

Alternatively, if the pickup proton ring distribution generates lower hybrid waves, they could heat electrons. The lower hybrid heating is inefficient unless the Alfvén speed is large (Omelchenko et al. 1989; Caems & Zank 2002), but the Alfvén speed downstream of SNR shocks is very poorly known. In the absence of information about $V_A$, one cannot make quantitative predictions. In Tycho’s SNR, which has a large neutral fraction in the preshock gas, the observed low electron temperature precludes efficient transfer of energy to the electrons if $V_A > 0.1V_S$.

3.5. Downstream Heating of Heavy Ions

Other elements with ionization potentials at least as large as that of hydrogen will be partially neutral in the preshock gas. They will also be ionized and picked up except that they will be more likely to undergo electron or proton collisional ionization rather than charge transfer, so the process will occur over a thicker region behind the shock. Thus O, N, and especially Ne and He should initially form ring distributions and be picked up by the plasma. As with the protons, the initial width of the ring varies as $\sin \theta$ and the initial speed along the field as $\cos \theta$.

Heavy ions present in the upstream plasma can also have peculiar downstream distributions due to their passage through the shock. They are decelerated by the electric potential jump associated with the shock, and because of their large mass to charge ratios they are decelerated less than the protons. Fuselier & Schmidt (1997) find that the initial ring velocity in this case is

$$V_\perp = V_s \left\{ (m/q - 1) + 1/16 \right\}^{1/2}$$

for a strong perpendicular shock. Thus we expect that heavy ions passing through the shock will have values of $V_\perp$ between $V_s$ and $3V_s/4$. A few observations exist to test this expectation. The line widths of C iv and He ii lines in the Hopkins Ultraviolet Telescope spectrum of SN 1006 (Raymond et al. 1995) are the...
same as the width of Hα within substantial uncertainties, and the O vi line observed with FUSE is consistent with the same width (Korreck et al. 2004). Ghavamian et al. (2002) find that the preshock neutral fraction of H is about 0.1, while that of He is at least 0.7. Since C has a lower ionization potential than H, and O has the same ionization potential has H, these elements also have small preshock neutral fractions. Thus C and O should have larger values of \( V_\perp \) than H, while He should be primarily a pickup ion distribution. Unfortunately, the 10% to 30% uncertainties in the line widths preclude a definitive comparison, but with somewhat higher quality profiles for the UV lines one could begin to constrain the magnetic field direction.

3.6. Cosmic-Ray Modified Shocks

Except for some consideration of magnetic field amplification, the discussion above assumes a simple magnetohydrodynamic shock. However, both observations and theory (e.g., Drury & Völk 1981; Malkov et al. 2000; Warren et al. 2005) indicate that a substantial fraction of the energy dissipated in the shock, as much as 80%, can be converted to cosmic rays. This results in a “modified shock” structure with several interesting features: (1) a particle velocity distribution such as a Maxwellian with a power-law tail, (2) a smooth transition rather than a sharp shock jump, (3) a compression ratio higher than the hydrodynamic factor of 4, and (4) a lower proton temperature for a given shock speed, since less energy is available to heat the gas.

The Balmer line profiles are not expected to reveal the nonthermal tails predicted for strong diffusive shock acceleration of cosmic rays, since only a very small fraction of the particles (∼10⁻³) are accelerated. Also, the charge transfer cross section declines rapidly at speeds above about 2000 km s⁻¹ (e.g., Schultz et al. 2008), so the faster protons are less likely to produce broad-component neutrals. Therefore, direct detection of the power-law tail will be very difficult.

The smooth transition could change the profile in a manner incompatible with observations, in that the gradually increasing temperature would give a composite Hα profile which is the sum of profiles formed at all the temperatures in the shock transition. It would probably not resemble the easily separable broad and narrow component profiles observed. This difficulty would be avoided if the smooth transition occurs on a length scale smaller than the length scale for charge transfer, since few broad-component neutrals would form in the intermediate temperature region. The length scale for a modified shock is \( V_\perp / \kappa \), where \( \kappa \) is the cosmic-ray diffusion coefficient. The charge transfer length scale is \( V_\perp / (n_p q_{CT}) \), where \( q_{CT} \) is the charge transfer rate coefficient. Since \( q_{CT} \sim 3 \times 10^{-7} \text{ cm}^3 \text{ s}^{-1} \) in the downstream plasma, \( \kappa \) should be smaller than about 10⁻³ \( \text{ cm}^2 \text{ s}^{-1} \). Values of \( \kappa \) of this order are required to accelerate cosmic rays to high energies within an SNR lifetime, but they are comparable to the Bohm limit, and therefore at the low end of the range of plausible values.

A high compression ratio, say 7 rather than the usual 4, would mean that the narrow component neutrals move at \( 6V_\perp /7 \) relative to the postshock gas, rather than \( 3V_\perp /4 \), so the PUI component will have larger initial parallel and perpendicular velocities by 14%. On the other hand, if a large fraction of the shock energy goes into nonthermal particles, the thermal speed of the protons will be reduced by a factor \((1 + P_C/P_G)^{-1/2}\), where \( P_C \) and \( P_G \) are the cosmic-ray and gas pressures. If \( P_C \) is comparable to \( P_G \), the thermal part of the line width will be seriously affected and the shock speed will be underestimated if \( P_C \) is assumed to be small. Most of the Balmer line filaments studied to date show very weak radio emission (e.g., the northwest filament in SN 1006 and the northern filament in the Cygnus Loop; Ghavamian et al. 2001, 2002), so \( P_C/P_G \) is probably small.

4. APPLICATION TO TYCHO’S SNR

Tycho’s supernova remnant presents a good opportunity to search for the effects described above because of its relatively high preshock neutral fraction (Ghavamian et al. 2000), the excellent high- and low-resolution spectra of knot g (Smith et al. 1991; Ghavamian et al. 2001; Lee et al. 2007), and the extensive X-ray and radio studies of both the thermal and nonthermal shocks (Dickel & Jones 1985; Dickel et al. 1991; Hwang et al. 2002; Warren et al. 2005; Bamba et al. 2005). The preshock density is approximately 1 cm⁻³, the preshock neutral fraction is approximately 0.85 and the shock speed is approximately 2000 km s⁻¹ (Ghavamian et al. 2000, 2001). The magnetic field is likely to be amplified in strong SNR shocks (e.g., Lucek & Bell 2000; Vink & Laming 2003), but its strength is not accurately known. Nonthermal synchrotron emission from nearby parts of the blast wave of Tycho’s SNR, implies that the magnetic field is on the order of 100 μG = 1B₁₀⁰ (Warren et al. 2005) yielding an Alfvén speed of approximately 100 km s⁻¹. The field direction is not known with certainty, although Dickel et al. (1991) show that the polarization indicates a predominantly radial field on scales of a few arcseconds behind the shock. The thermal pressure implied by the Rankine-Hugoniot jump conditions with the shock speed and the preshock density above yields a plasma \( \beta \) of 12/B₁₀⁰⁻¹.

There is a significant shift between the centroids of the broad and narrow components of the Hα profiles in Tycho. Smith et al. (1991) and Ghavamian et al. (2001) found shifts between the broad and narrow components of Hα of 240 ± 60 and 132 ± 35 km s⁻¹, respectively, for two slit positions in knot g. Smith et al. interpreted the shift as an indication that the shock normal does not lie in the plane of the sky, so that the shift represents a small component of the postshock plasma speed. This interpretation is consistent with the observation of Lee et al. (2004), who showed that the centroid of the narrow component is shifted with respect to the centroid of the ambient gas in that region (although there is some uncertainty about the size of this shift; Lee et al. 2007). However, the shock normal cannot be very far from the plane of the sky, since very strong limb brightening is required to account for the observed brightness of knot g.

Alternatively, it is possible that the shift between broad and narrow component centroids is related to the projection of \( v_{\text{bulk}} \) onto the line of sight. The shift is limited to approximately \( V_A \), so a shift of the magnitude measured would require that the projection of the magnetic field direction onto the direction parallel the line of sight be fairly large, and therefore \( \theta \) must be near 90°. Within the limits of the data now available, we cannot tell whether the shift between broad and narrow centroids is essentially a geometrical effect, as proposed by Smith et al. (1991) or a result of the pickup ion bulk speed discussed above.

A second puzzle relates to the nature of turbulence downstream from the shock. If the 100 μG field is generated by turbulent amplification in the shock front, it will be fairly disordered. The nonresonant mechanism proposed by Bell (2004) predicts that the scale of the turbulence is smaller than the gyroradius of cosmic-ray protons (Zirakashvili et al. 2008), and generally yields a perpendicular shock. Compression by the shock would also make the mean field direction more perpendicular to the shock normal. Giacalone & Jokipii (2007) and Zirakashvili et al. (2008) study the effects of density inhomogeneities on magnetic field generated downstream of the shock. Both works find significant magnetic
amplification, and Zirakashvili & Ptuskin (2008) remark that the magnetic field component parallel to the shock normal is more enhanced. The interaction between the pickup ions and the field also tends to bend the field toward the shock normal, and the observed field in Tycho’s SNR is nearly radial at the edge of the SNR (Dickel et al. 1991). A turbulent field would suggest that the pickup process occurs over a large range of $\beta$, smearing out the profile as in Figure 5d. Detection of a non-Gaussian profile in H$\alpha$ would provide some idea of the nature of the turbulence. This will require very good data and careful assessment of the instrument profile and the background level, however, and existing data do not provide useful constraints.

5. DISCUSSION

5.1. Caveats

There are several qualifications to the analysis presented here. One is the use of PUI analysis based on Alfvén waves, which is appropriate for a cold plasma. As mentioned above, $\beta$ is around 12 for Tycho’s SNR, and that will be typical for the strong shocks seen as Balmer line filaments. Thus, other wave modes may be important. It is unknown whether they will tend to change the directions, rather than the energies, of the protons in the way that Alfvén waves do. It is also possible that they will provide better coupling to the electrons.

Another question is whether the amplified B field behind the shock is strongly turbulent on small scales. If so, PUI would be generated over a broad range of angles (Isenberg 1999; Németh et al. 2000) tending to wash out any line-shift signature in the H$\alpha$ profile. The polarization measurements of Dickel et al. (1991) indicate that the field is reasonably well ordered on the scale of their resolution, but it could be highly random on the 0.1$^\circ$ scale over which the H$\alpha$ is produced.

Finally, there is the question of momentum conservation when a significant fraction of the downstream plasma has been picked up and streams along an oblique magnetic field. In this case, the thermal plasma would presumably act to cancel the transverse momentum, resulting in a rotation of the field toward the shock normal. We plan to quantitatively investigate this interaction in the near future. The resolution may lie in the density gradient of the pickup ions, but further calculations are needed.

5.2. Implications for Balmer Line Filament Analysis

If the pickup ions provide a significant contribution to the H$\alpha$ profile, values of $V_\parallel$ derived from Gaussian fits are somewhat in error. This error would propagate into distances derived by combining shock speeds derived from the Balmer line profiles with proper motions (e.g., Winkler et al. 2003). The modifications are probably not severe, and in cases such as SN 1006, where the preshock neutral fraction is only 10% and the contribution of pickup ions to the Balmer line profiles is only 5%, they would be completely negligible. In cases where the preshock neutral fraction is of order 50%, as much as 25% of the broad-component emission could arise from atoms produced by charge transfer from pickup ions. In such cases $V_\parallel$ would probably be underestimated. On the other hand, waves emitted by the pickup ions as they isotropize could heat the protons and lead to a compensating effect.

If non-Maxwellian distributions can be observed by way of distortions of the H$\alpha$ profiles of nonradiative shocks, they could contain unique information about the strength and direction of the magnetic field and the level of turbulence in the region where the H$\alpha$ emission arises. The most promising SNR where non-Maxwellian distributions might be found is probably Tycho, thanks to its large neutral fraction and relatively bright H$\alpha$ emission.

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