The pre-shock gas of SN1006 from HST/ACS observations

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ABSTRACT

We derive the pre-shock density and scale length along the line of sight for the collisionless shock from a deep HST image that resolves the H\(_\alpha\) filament in SN1006 and updated model calculations. The very deep ACS high-resolution image of the Balmer line filament in the northwest (NW) quadrant shows that \(0.25 \leq n_0 \leq 0.4\) cm\(^{-3}\) and that the scale along the line of sight is about \(2 \times 10^{18}\) cm, while bright features within the filament correspond to ripples with radii of curvature less than 1/10 that size. The derived densities are within the broad range of earlier density estimates, and they agree well with the ionization time scale derived from the Chandra X-ray spectrum of a region just behind the optical filament. This provides a test for widely used models of the X-ray emission from SNR shocks. The scale and amplitude of the ripples are consistent with expectations for a shock propagating though interstellar gas with \(\sim 20\%\) density fluctuations on parsec scales as expected from studies of interstellar turbulence. One bulge in the filament corresponds to a knot of ejecta overtaking the blast wave, however. The interaction results from the rapid deceleration of the blast wave as it encounters an interstellar cloud.

Subject headings: ISM:individual(SN1006)--supernova remnants--shock waves--optical:ISM

1. Introduction

SN1006 (G327.6+14.6) is one of the best SNRs for studying the physics of collisionless astrophysical shocks, in particular the acceleration of non-thermal particles. It is a nearby Type Ia supernova remnant at a distance of 2.1 kpc (the distance we assume throughout) with a diam-
eter of $\sim 18$ pc (Winkler, Gupta & Long 2003) and a shock speed in the 2500 - 2900 km s$^{-1}$ range (Ghavamian et al. 2002; Heng & McCray 2006). The remnant has a high Galactic latitude and modest foreground reddening, $E(B-V)=0.11 \pm 0.02$ (Schweizer & Middleditch 1980).

SN1006 has been observed at radio (Reynolds & Gilmore 1993; Moffett, Goss & Reynolds 1993), optical (Ghavamian et al. 2002; Kirshner, Winkler & Chevalier 1987; Smith et al. 1991), ultraviolet (Raymond, Blair & Long 1995; Korreck et al. 2004) and X-ray (Koyama et al. 1995; Winkler, Gupta & Long 2003; Long et al. 2003; Bamba et al. 2003; Dyer et al. 2004) wavelengths. Pure Balmer line filaments were found in the optical by van den Bergh (1976). In the radio and X-ray, the remnant has a limb-brightened shell structure with cylindrical symmetry around a SE to NW axis probably aligned with the ambient galactic magnetic field (Reynolds 1996; Jones & Pye 1989). The NE shock front of SN1006 shows strong non-thermal X-ray emission (Koyama et al. 1995; Winkler, Gupta & Long 2003; Long et al. 2003; Bamba et al. 2003; Dyer et al. 2004) while the NW shock shows very little non-thermal emission at radio or X-ray wavelengths. On the other hand, the pre-shock density is several times higher in the NW than the NE (Korreck et al. 2004). Knots of X-ray emission from shocked SN ejecta are scattered through the interior of the remnant (Long et al. 2003; Vink et al. 2003).

A Balmer line filament defines the blast wave in the northwest quadrant of SN1006, and the H$\alpha$ profile provides diagnostics for the shock speed and ion-electron thermal equilibration. The H$\alpha$ emission from a Balmer-dominated shock has a two component profile (Chevalier & Raymond 1978). The broad component is due to charge exchange between neutrals and protons, which produces a population of neutrals at nearly the post-shock proton temperature. The narrow component is produced when cold ambient neutrals pass through the shock and emit line radiation before charge transfer or ionization occurs. The ratio of the broad to narrow flux is sensitive to the electron and ion temperatures.

The FWHM of H$\alpha$ broad component is $2290 \pm 80$ km s$^{-1}$, and models imply a shock speed of $v_{\text{shock}} = 2890 \pm 100$ km s$^{-1}$ for a shock with little electron-ion equilibration (Ghavamian et al. 2002). However, new models incorporating some additional physics obtain a lower shock speed of $2509 \pm 111$ km s$^{-1}$ (Heng & McCray 2006).

The pre-shock density, $n_0$, is an important parameter for understanding the evolution of SN1006, as well as for interpreting the X-ray spectra in terms of ionization time scale and determining the relative contributions of shocked ISM and SN ejecta to the X-ray emission. The density could also be important for attempts to understand the high ratio of non-thermal to thermal X-ray emission in this SNR. Estimates of $n_0$ cover a wide range, from 0.05-0.1 cm$^{-3}$ based on the global X-ray emission (Hamilton, Sarazin & Szymkowiak 1986) to 1 cm$^{-3}$ based on interpreting the scale over which the X-rays brighten as the length scale for ionization of the shocked plasma (Winkler & Long 1997). A related parameter is the length scale along the line of sight. The ripples in the SNR blast wave could in principle result from density inhomogeneities in the ambient...
medium or from knots of SN ejecta overtaking the blast wave. ISM density fluctuations have been inferred for a section of the non-radiative shock in the Cygnus Loop (Raymond 2003), while an ejecta knot is clearly the cause of one bulge in the Hα filament of SN1006 (Long et al. 2003; Vink et al. 2003). The issue is important for estimating the amplitude of interstellar turbulence on sub-parsec scales and for the interpretation of the distance between the blast wave and the reverse shock in terms of particle acceleration (Warren et al. 2005).

In this paper we use an Hα image obtained with the ACS imager on the Hubble Space Telescope to determine the pre-shock density and the length scale along the line of sight. This is possible because the ACS images resolve the thickness of the narrow zone behind the shock where hydrogen atoms are excited and ionized, and that thickness scales inversely as the pre-shock density. We have computed new models of the Hα emissivity as a function of distance behind the shock taking into account recent results by Heng & McCray (2006). We discuss the observations in the next section, then compare with models to derive the shock parameters. Section 4 provides a limit on the brightness of any shock precursor, compares the densities with other estimates and discusses the implications for other analyses of SN1006 observations. Section 5 summarizes the conclusions.

2. Observations

The Hubble Space Telescope’s ACS Wide Field Camera (WFC) imaged a full field of 202 x 202 arcsec² at coordinates α<sub>2000</sub> = 15ʰ 2ᵐ 19.02ˢ, δ<sub>2000</sub> = -41° 44′ 48.4″ on 9 orbits from 15-17 February 2006. Exposures with durations of 2,746.0 s, 2,848.0 s, and 2,828.0 s were obtained for each subset of 3 orbits, for a combined 25,266 second exposure. The exposures were taken with the F658N H-alpha filter, which has a flat response at wavelengths above about 6558 Å, drops to half the peak transmission at about 6548 Å and 20% of the peak transmission at 6540 Å. This means that it passes the narrow component, all the red wing of the broad component, and about half the blue wing of the broad component, or about 90% of the Hα emission.

The image was centered on the position where Ghavamian et al. (2002) obtained a low dispersion spectrum and Sollerman et al. (2003) obtained a high dispersion spectrum, so we are able to use the shock speed, neutral fraction and electron-ion equilibration derived from those observations. The position was also observed in the ultraviolet with the Hopkins Ultraviolet Telescope (Raymond, Blair & Long 1995; Laming et al. 1996) and with FUSE (Korreck et al. 2004), so that we can use the information derived in those papers about ion-ion thermal equilibration to constrain model parameters. The Hα filament also defines the outer boundary of position NW-1 in the X-ray spectral analysis of Long et al. (2003), who found the spectrum to be consistent with thermal emission from shocked interstellar gas.

The raw data were combined and reduced with the standard ACS calibration pipeline (CALACS), involving bias/dark-current subtraction, flat-fielding, image combination, and cosmic-ray rejection (Sirianni et al. 2005), then ‘drizzled’
(Fruchter and Hook 2002) onto a 0.03 arc-sec pixel scale with the task ‘multidrizzle’ to correct for geometric distortion and improve the sampling of the point spread function (Koekemoer et al. 2002).

Figure 1 shows the HST image overlaid on the Chandra X-ray image. The morphology of the filament is clearly that of a rippled sheet seen edge-on, with the bright rims corresponding to tangencies to the line of sight (Hester 1987). For the present purposes we are interested in the simplest tangencies, since those are amenable to modeling. The bulge near the SW corner of the image is morphologically similar to a larger, brighter region farther to the SW where a clump of ejecta is overtaking the shock (Long et al. 2003; Vink et al. 2003), but it shows only a slight X-ray enhancement. The shock morphology in the bulge is more complex, so this paper concentrates on the smoother regions of the filament.

IDL was used to extract and plot the curve of the shock front spanning the drizzled image and to find the approximate direction perpendicular to the shock. At each of 40 positions we extracted the spatial profiles across the shock for a range of angles near the initial estimate and selected the the profile showing the narrowest Hα peak as the one closest to the shock normal direction. Many of the profiles suffer from low signal to noise or from complexity due to several tangencies to the line of sight. We have selected 8 profiles with bright, simple Hα peaks for further analysis. In particular, we model sections of the trailing edge of the filament in regions corresponding to sections F, G and H of the (Winkler, Gupta & Long 2003) proper motion analysis. Figure 2 shows the boxes used to extract spatial profiles, starting with profile 8 in the upper left and ending with profile 29 in the lower right. The profiles were extracted using boxes 4.5″ wide and 9″ long. Their positions and position angles are shown in Table 1. The profiles extracted were similar to those used by (Winkler, Gupta & Long 2003) for measuring the proper motion of the filament; here, however, the goal was to determine the width, not the position, of the filament.

3. Analysis and Results

To interpret the images we compute models of the Hα brightness behind a curved shock, convolve the model intensity distribution with the ACS point spread function, and compare the models to the observations. In general, the pre-shock density controls the brightness drop off behind the peak, because the thickness of the emission region is inversely proportional to the density. The radius of curvature of the shock determines the fall off ahead of the peak for the concave outward filaments that we model here. The absolute intensity scales approximately as $n_0^2f_{\text{neut}}R^{1/2}$, where $n_0$ is the pre-shock density, $f_{\text{neut}}$ is the pre-shock neutral fraction, and $R$ is the radius of curvature of the shock.

3.1. Model Calculations

We start with model calculations similar to those of Laming et al. (1996). Figure 3 shows the Hα emissivity as a function of distance behind the shock for a 2900 km s$^{-1}$ shock model with pre-shock density $n_0 = 0.25$ cm$^{-3}$, a neutral fraction of 0.1, and a ratio $T_e/T_p = 0.05$.
at the shock front. The model follows neutral hydrogen as it passes through the shock and undergoes collisional excitation and ionization by protons and electrons as well as charge transfer with post-shock protons. The atomic rates are described by Laming et al. (1996), and Coulomb collisions slowly transfer energy from the ions to the electrons. The radiative transfer involved in the conversion of Ly$\beta$ photons to H$\alpha$ photons, important for the narrow component, is described in Laming et al. (1996). A fraction of the H$\alpha$ arises from converted Ly$\beta$ photons, and those H$\alpha$ photons are produced over a scale of about 1 Ly$\beta$ mean free path. That scale is about 0.1", which is small enough compared to the observed filament widths that we ignore it.

Evidence for a shock precursor has been reported for a number of non-radiative shocks from low ionization emission lines (Hester, Raymond & Blair 1994; Sollerman et al. 2003), from the velocity widths of their narrow components (Smith et al. 1994; Hester, Raymond & Blair 1994), and from the spatial distribution of the narrow component emission (Lee et al. 2006). The narrow component in SN1006 shows no broadening beyond that expected for the ambient ISM (Sollerman et al. 2003), so we do not include any precursor emission in the models.

Recently, Heng & McCray (2006) investigated the consequences of the sharp decline of the charge transfer cross section at speeds above about 2000 km s$^{-1}$ for the Balmer line profiles. They estimated a shock speed of 2509$\pm$111 km s$^{-1}$ from the Balmer line profile presented by Ghavamian et al. (2002), as opposed to the value 2890$\pm$100 km s$^{-1}$ found by Ghavamian et al. Both values apply to the case of little ion-electron thermal equilibration in the shock. Strong equilibration is ruled out by the X-ray spectrum of Long et al. (2003) and by the combination of broad to narrow intensity ratio given by Ghavamian et al. (2002) and the Ly$\beta$ radiative transfer calculations of Laming et al. (1996). The smaller shock speed of Heng & McCray (2006) would decrease the distance scale of the H$\alpha$ emission behind the shock. However, it would also imply a smaller distance for SN1006 based the combination of the proper motion and the shock speed (Winkler, Gupta & Long 2003), so the angular width of the emission region would be unchanged to first order.

There is another important implication of the work of Heng & McCray (2006) for the present study. The rapid drop in charge transfer cross section with increasing velocity means that neutrals are more likely to undergo charge transfer with protons moving away from the shock than with protons moving toward the shock. While the velocity dependence of the cross section was included in earlier models, the anisotropy of the resulting H I velocity distribution was not. Thus the earlier models implicitly assumed that the broad component neutrals move away from the shock at $V_s/4$, the same speed as the post-shock protons. By integrating the product of velocity times charge transfer cross section, $\sigma_{c2}v$ (Barnett 1990), over Maxwellian distributions at the post shock temperatures, we find that after 1 charge transfer event the average neutral is moving away from the shock at 1500 km s$^{-1}$ behind a 3000
km s$^{-1}$ shock, rather than the 750 km s$^{-1}$ of the ionized gas. For a 2500 km s$^{-1}$ shock, the neutrals move at 1100 km s$^{-1}$ instead of 625 km s$^{-1}$. Thus for the interesting range of shock speeds, the neutrals move away from the shock twice as fast as is assumed in the model shown in Figure 3. The relative velocity is much smaller for the second charge transfer event, so after two charge transfers the neutrals have a speed closer to that of the downstream plasma. Kevin Heng (2007, private communication) has provided the average downstream speed of the broad component neutrals computed by the Heng & McCray (2006) model code. For the 2500 to 3000 km s$^{-1}$ velocity range it is 1.32 times the plasma speed. Therefore, for comparison to observations we stretch the spatial scale of the broad component emission shown in Figure 3 by a factor of 1.32. Particle conservation implies that the neutral density is decreased by the same factor, so the broad component emissivity at each point is reduced by a factor of 1.32. Finally, for comparison with the observations we multiply the broad component emission by 0.75 to account for the drop of sensitivity in the blue wing resulting from the transmission of the F658N filter.

To model the geometry of the filament, we assume a shock surface that is concave outward with radius of curvature R. The H$\alpha$ emissivity from the planar model extends behind the shock at each point. Numerical integration then gives the brightness as a function of position relative to the tangent point of the shock. For comparison with the observations, we convolve the model emissivity with the ACS point spread function. In order to properly account for the pixel sampling in cuts made at about 45° to the rows and columns of the detector, we measured the Gaussian widths of stars near the filament (2.31 pixel FWHM), then placed a dense series of circular Gaussians along a 45° line, extracted the profile perpendicular to that line, and measured a slightly broader 2.43 pixel width. This Gaussian is convolved with the models for comparison with the observed spatial profiles.

Figure 4 is a schematic diagram of the geometry we imagine in a plane that includes the line of sight (dashed line) and a radial vector from the center of the SNR. The light line shows a large scale ripple in the shock front, and we have superposed a smaller scale ripple to obtain the shape of the heavier curve that is shaded toward the inside of SN1006. The shading indicates the H$\alpha$ emissivity, which fades gradually from the shock front towards the inside of the SNR. The trace in the lower right indicates the H$\alpha$ brightness obtained for a cut across the tangent point of the shock by integrating the H$\alpha$ emissivity along different lines of sight.

3.2. Comparison of Models and Observations

Figure 5 compares a grid of models with different $n_0$ and R to the spatial profile at position 10. The sharp spikes ahead of the H$\alpha$ peak are faint stars in the extraction region. The models have been scaled to match the peak H$\alpha$ brightness of the filament by simply adjusting the neutral fraction. Neutral fractions above 1 are obviously unphysical, so models with low $n_0$ and small R are ruled out. Ghavamian et al. (2002) estimated a pre-
shock neutral fraction of 0.1 from the ratios of He I and He II lines to Hα, so we take the permitted range of neutral fractions to be $0.05 \leq f_{\text{neut}} \leq 0.2$. Figure 3 shows that models with $n_0$ below about 0.30 cm$^{-3}$ fall off too slowly behind the shock, while the models with $n_0$ above about 0.35 cm$^{-3}$ give too sharp a peak. The $R=5 \times 10^{16}$ cm model comes closest to matching the observed profile. Models with smaller R predict Hα emission fainter than observed. We conclude that $0.3 \leq n_0 \leq 0.35$ and $10^{16.5} \leq R < 10^{16.8}$ cm.

Figure 6 shows the analogous plots for position 28. The peaks in this section of the filament are both brighter and broader, with a fairly constant Hα intensity ahead of the brightness peak. None of the models match exactly, probably because the rippled sheet does not follow the assumed shape of an arc of a circle. From Figure 6 we conclude that $n_0$ must be greater than 0.25 cm$^{-3}$ to avoid a long tail toward the inside of the remnant, but that densities above 0.4 produce too sharp a peak. R must be less than $2 \times 10^{17}$ cm, because larger radii of curvature predict a shoulder on the outer side of the spatial profile that exceeds the observations, while R less than $0.7 \times 10^{17}$ cm requires unacceptably high values of $f_{\text{neut}}$ to match the brightness. We conclude that the acceptable ranges are $0.25 \leq n_0 \leq 0.35$ and $0.7 \times 10^{17} \leq R \leq 1.5 \times 10^{17}$ cm. We note, however, that the agreement between the model spatial profiles and the observations is not as good as at position 10. Based on Figure 2, it seems possible that the bright filament at position 28 contains more than one tangency to the line of sight, broadening the spatial profile and increasing the total brightness. Thus the upper limit on $n_0$ and the lower limit on R are less secure than in the case of position 10.

Table 1 presents the ranges of $n_0$ and R derived from other positions along the filament. We did not attempt to model other positions where the emission peak is faint or where complex morphology indicates a more complex structure than can be approximated by a simple curved sheet. The profiles of positions 8 through 11 are qualitatively similar to that of position 10, and those of positions 26 through 29 are like that of position 28.

4. Discussion

4.1. Pre-shock density

The densities near 0.3 cm$^{-3}$ that we derive fall in the middle of the range of previous values. Hamilton, Sarazin & Szymkowiak (1986) estimated 0.05-0.1 cm$^{-3}$ from the global X-ray spectrum. Since the pre-shock density in the NE, and quite likely the rest of the remnant, is about 2.5 (Long et al. 2003) to 4 (Korreck et al. 2004) times smaller than in the region we observed, the Hamilton, Sarazin & Szymkowiak (1986) estimate is consistent with our results, even though most of the X-ray emission was subsequently shown to be non-thermal in nature. Winkler & Long (1997) obtained a pre-shock density near 1.0 from the spatial profile of the X-ray emission, but Long et al. (2003) found $n_0 \approx 0.25$ from the value of $n_{\text{e}} t$ obtained from the Chandra spectrum of their region NW-1, which lies immediately behind the region of the Balmer line filament we observed. The Chandra spectrum showed solar abundances, which is consistent with the inter-
pretation of shocked interstellar gas, and the temperature of 0.7 keV is consistent with very inefficient thermal equilibration between ions and electrons. Thus the present results agree well with the results of shock wave models of the X-ray spectra and confirm the parameters derived. However, as Long et al. (2003) point out, the shock models did not provide an acceptable \( \chi^2 \) fit to the data, so some aspect of the physics remains to be understood. In particular, with \( n_0 \) as an independently measured quantity rather than a free parameter, reanalysis of the Chandra spectrum might be able to place better limits on the non-thermal emission in the NW part of SN1006.

Another density estimate for the NW region of SN1006 was obtained by Laming et al. (1996), who found that the relative intensities of the UV lines could be explained if only about half the O VI emission fell within the aperture of the HUT telescope. This would require an ionization length for the O VI of about \( 10'' \), or \( n_0 \sim 0.04 \text{ cm}^{-3} \). This interpretation is not consistent with the values of \( n_0 \) derived for the same region from the HST image, so we conclude that there is a problem either with the models of Laming et al. (1996), or perhaps more likely with the reddening correction in the far UV.

A density estimate that is independent of SN1006 itself comes from H I 21 cm observations by Dubner et al. (2002). An H I feature with a column density of \( 7 \times 10^{20} \text{ cm}^{-2} \) at a velocity of \(-6 \text{ km s}^{-1}\) lies just outside the NW rim of SN1006. While the velocity does not correspond to the Galactic rotation value at the distance to SN1006 \((-25 \leq V_{LSR} \leq -16 \text{ km s}^{-1})\), the SNR is far enough from the plane that the velocity could easily differ. Dubner et al. (2002) estimate a neutral hydrogen density of \( 0.5 \text{ cm}^{-3} \) which with the low neutral fraction from Ghavamian et al. (2002) would imply a total density of \( 5 \text{ cm}^{-3} \), well above the values we derive. We conclude that either SN1006 is not interacting with the cloud identified by Dubner et al., or that the shock has only reached the low density outskirts of the cloud.

4.2. Length scales

The length scale given by the radius of curvature is considerably shorter than the length of the filament itself. The more or less straight portion of the H\( \alpha \) filament extends for perhaps \( 7'' \), or about 4 pc, roughly 100 times typical radius of curvature derived for the ripples. The actual line of sight scale of the filament is several times that of the bright rim at the trailing edge of the filament. The region ahead of the trailing bright rim at position 28 has a nearly constant surface brightness of \( 2 - 3 \times 10^{-5} \) photons cm\(^{-2} \) s\(^{-1} \) \( n''^{-2} \). For \( n_0 = 0.3, f_{\text{neut}} = 0.1 \) and \( V_s = 2900 \text{ km s}^{-1} \), this implies an angle of 6 to 10 degrees between the shock and the line of sight. The roughly constant intensity region is about \( 2.8 \times 10^{17} \text{ cm} \) in radial extent, so the range of angles implies a depth along the line of sight between 1.5 and \( 2.3 \times 10^{18} \text{ cm} \), or about a tenth the scale of the filament in the plane of the sky. The \( 10^{18} \text{ cm} \) scale corresponds to the smoother curve in the schematic diagram in Figure 4, while the \( 10^{17} \text{ cm} \) scale derived from the H\( \alpha \) brightness profiles corresponds to the smaller scale ripple superposed to obtain the shock geometry shown in the schematic.
Even the larger scale inferred for the direction along the line of sight is several times smaller than the length of the filament in the plane of the sky. Very faint Hα emission, which is not apparent in Figure 2, is seen in the very deep Hα image of Winkler, Gupta & Long (2003) extending out ahead of the bright filament (their Figure 5). This is probably a shock in lower density gas that may be farther from tangency with the line of sight, and it probably extends for a distance comparable to the length of the filament.

Figure 2 shows that ripples on the scale of $10^{18}$ cm can be seen in the direction along the filament, for instance between the two boxes where radial profiles were extracted. Ripples on the $10^{17}$ cm scale are not apparent, perhaps because a $10^{17}$ cm ripple with 10% amplitude would be only a few resolution elements radially in Figure 2. However, such small scale rippling undoubtedly contributes to the widths of the Hα brightness peaks and prevents them from being as sharp as the model peaks, as is particularly apparent in the position 28 profile. It is also quite likely that the ripples are not isotropic. If the magnetic field lies near the plane of the sky in the NE-SW direction, then density structures would be elongated in that direction and smaller scales would appear along the line of sight. There is some evidence that the field does lie in this direction based on the cap-like morphology of the non-thermal X-ray emission (Willingale et al. 1996), but there is also a suggestion that the field lies in the SE-NW direction based on the relative temperatures of protons and oxygen ions (Korreck et al. 2004).

If we attribute the $\sim 2 \times 10^{18}$ cm scale length of the ripples to density fluctuations in the interstellar gas, we can estimate the amplitude of the density fluctuation from the amplitude of the ripple. The amplitude of the ripple is about one tenth the wavelength, and that should be about equal to $\delta V/V$. For constant ram pressure, $nV^2$, this requires density fluctuations of about 20%. As was found for similar ripples in the blast wave of the Cygnus Loop, this agrees reasonably well with the expectations from the spectrum of interstellar turbulence (Minter & Spangler 1997; Raymond 2003). However, the smaller scale ripples revealed by the $10^{17}$ cm radius of curvature also seem to have amplitudes of order 1/10 the wavelength, and a Kolmogorov spectrum of density fluctuations from the turbulent cascade would lead one to expect a smaller amplitude (Minter & Spangler 1997). Beresnyak & Lazarian (2006) show that the spectrum of density fluctuations may be considerably flatter than the Kolmogorov spectrum.

One feature in the filament is probably not due to density fluctuations in the ISM, however. The bulge near the western edge of the filament in Figure 2 is very similar to one farther west along the filament that coincides closely with a bright knot of X-ray emission with enhanced elemental abundances (Long et al. 2003; Vink et al. 2003). The X-ray knot (position NW-2 of Long et al. (2003)) is clearly a knot of ejecta overtaking the blast wave. The bulge at the SW corner of the ACS image is probably a similar structure with lower X-ray contrast due to its smaller size and perhaps differences in density, ionization time scale and abundances. According
to hydrodynamic simulations of Type Ia SNRs, ejecta knots form at the Rayleigh-Taylor unstable contact discontinuity, but they reach at most 87% of the blast wave radius (Wang & Chevalier 2001). Thus the ejecta knots should be over a parsec, or about 2' behind the Balmer filament. Warren et al. (2005) have pointed out that if a substantial fraction of the energy dissipated by a shock goes into accelerating cosmic rays, the ejecta knots can come much closer to the outer shock. In the case of the bulge in the southwestern corner of the HST image and the X-ray knot farther to the SW, the lack of synchrotron emission at radio and X-ray wavelengths indicates that little energy goes into cosmic rays. Instead, since the blast wave encountered the dense gas in the NW sector of SN1006 only about 180 years ago (Long et al. 2003), the ejecta knots have undoubtedly overtaken the blast wave because the blast wave decelerated when it encountered denser gas. This has an important implication for analyses of the fraction of shock energy that goes into cosmic rays. Warren et al. (2005) show that ejecta knots in Tycho’s SNR come much closer to the blast wave than predicted by Wang & Chevalier (2001), and they interpret this in terms of energy that goes into accelerating particles to high energies. That argument can be applied to most of Tycho’s SNR, but regions where the SNR shell is flattened or where the Balmer line emission is especially bright should be avoided in the analysis, because those are regions where the shock has probably been decelerated by higher density gas.

4.3. Shock Precursor

Shock wave precursors have been inferred from anomalously high line widths of the narrow component Hα emission in a number of SNRs and attributed to heating in the precursor predicted by diffusive shock acceleration models or to broad component hydrogen atoms that overtake the shock and heat the upstream gas (Smith et al. 1994, Hester, Raymond & Blair 1994). The small width of the narrow component in SN1006 means that there is no evidence for such a precursor, but it is nevertheless worthwhile to place on limit on the emission from such a precursor. One expects a more or less exponential falloff of brightness ahead of the shock peak on a scale given by $\kappa/V_s$, where $\kappa$ is the cosmic ray diffusion coefficient, or by $(n_0\sigma)^{-1}$ where $\sigma$ is the charge transfer cross section. The former would be about 1'' for $\kappa \sim 10^{25}$ cm$^2$s$^{-1}$. For a speed near 3000 km s$^{-1}$ and the densities in Table 1, the latter would be about 0.6''. The brightness could be a significant fraction of the narrow component brightness, or up to half the total brightness of the filament.

The concave outward ripples we have analyzed so far are not appropriate for searching for a precursor, because the emission from the curved part of the shock front could easily resemble emission from a precursor. Instead the bright rims about 10'' ahead are convex outward ripples, so that any emission ahead of the peak would be due to a precursor. Spatial profiles do show shoulders of order 1'' wide ahead of the leading bright rims in several places. However, there is additional faint emission out ahead of the main filament along the entire region im-
aged (Winkler, Gupta & Long (2003), Figure 5). That suggests that the leading rim might be $S$-shaped along the line of sight rather than a convex outward arc, so the $H\alpha$ could be similar to that in the models described above (Figures 4 and 5). In particular, the sections of the filament that show an $H\alpha$ shoulder ahead of the peak emission seem to be the regions where the diffuse emission ahead of the filament is especially bright. Therefore, we can only place an upper limit on the precursor just ahead of the shock of about 1/3 the peak brightness. Stricter limits of about 1/10 the peak brightness can be placed in some sections. Given the lack of evidence for heating in a precursor in SN1006, this is not surprising. It does suggest, however, that morphology alone may not be enough to establish the existence of a precursor without some additional information such as $[N \text{ II}]$ or $[S \text{ II}]$ line emission (Hester, Raymond & Blair 1994), spatial separation of narrow and broad emission (Lee et al. 2006), superthermal $[N \text{ II}]$ line widths (Sollerman et al. 2003), or narrow component line widths of order 40 km s$^{-1}$.

### 4.4. Bulk velocity contribution to line widths

The widths of the $H\alpha$ and UV line profiles have been analyzed under the assumption that the broadening due to bulk motions in parts of the filament that are not quite tangent to the line of sight is small. The range of angles between the line of sight and the shock surface derived above for the region between the leading and trailing rims implies doppler shifts up to 1/6 the post-shock speed, or $V_s/8$. Making the extreme assumption that both red- and blue- shifts are present, and ignoring the contribution of the bright rims that are tangent to the LOS, the contribution of bulk motions as large as 370 km s$^{-1}$ could be present, or a full width of 750 km s$^{-1}$. With measured line widths of 2290 km s$^{-1}$ for $H\alpha$ (Ghavamian et al. 2002) and 2100 to 2600 km s$^{-1}$ for the UV lines (Raymond, Blair & Long 1995; Korreck et al. 2004), bulk motions contribute at most 6% to the measured line widths when added in quadrature to the thermal widths.

### 5. Summary

An HST image of the Balmer line filament in SN1006 resolves the region where neutral hydrogen is excited and ionized. The thickness of the ionization zone implies a total density of 0.25 to 0.40 cm$^{-3}$, roughly in the middle of the order of magnitude range of earlier density estimates. It agrees well with the density inferred by Long et al. (2003) from the ionization time scale of the X-ray emission just behind the Balmer line filament, providing confirmation for the shock wave models used to interpret the X-ray spectra. Ripples in the filament on parsec scales are consistent with those expected for a shock propagating through a medium with $\sim 20\%$ density fluctuations on a parsec scale, in accordance with measurements of turbulence in the ISM. The ripples on 10$^{17}$ cm scales have higher amplitude than expected for a Kolmogorov spectrum of density fluctuations, however. A bulge in the $H\alpha$ filament corresponding to a knot of ejecta shows that ejecta knots can overtake the outer SNR shock when the blast wave decelerates upon encountering a dense cloud.
The density estimates in this paper are based upon model calculations for the emission from non-radiative shocks. The models took recent improvements by Heng & McCray (2006) into account in an approximate way, but a more complete model would be valuable. Models of the 3D morphology of the filament that go beyond the simple shape assumed could improve the accuracy of the derived parameters, especially when spatially resolved spectra become available to pin down the additional parameters involved.

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Facilities: HST

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Table 1

Densities and radii of curvature from Hα spatial profiles

| Position | RA<sub>2000</sub> | δ<sub>2000</sub> | PA     | n<sub>0</sub> | R<sup>a</sup> |
|----------|------------------|-----------------|--------|-------------|-------------|
| 8        | 15<sup>h</sup>02<sup>m</sup>23.488<sup>s</sup> | -41°44′12.45″   | 152.15 | >0.35       | <0.4        |
| 9        | 15<sup>h</sup>02<sup>m</sup>23.136<sup>s</sup> | -41°44′14.62″   | 154.65 | >0.40       | <0.4        |
| 10       | 15<sup>h</sup>02<sup>m</sup>22.796<sup>s</sup> | -41°44′16.96″   | 154.65 | 0.30 - 0.35 | 0.3 - 0.6   |
| 11       | 15<sup>h</sup>02<sup>m</sup>22.450<sup>s</sup> | -41°44′19.29″   | 155.90 | >0.35       | <0.5        |
| 26       | 15<sup>h</sup>02<sup>m</sup>17.340<sup>s</sup> | -41°44′55.13″   | 153.40 | 0.25 - 0.35 | 2 - 5       |
| 27       | 15<sup>h</sup>02<sup>m</sup>17.014<sup>s</sup> | -41°44′57.91″   | 154.65 | 0.30 - 0.40 | 0.8 - 1.2   |
| 28       | 15<sup>h</sup>02<sup>m</sup>16.682<sup>s</sup> | -41°45′00.34″   | 153.40 | 0.25 - 0.35 | 0.7 - 1.5   |
| 29       | 15<sup>h</sup>02<sup>m</sup>16.340<sup>s</sup> | -41°45′02.74″   | 157.15 | 0.35 - 0.40 | 0.5 - 1     |

<sup>a</sup>10<sup>17</sup> cm
Fig. 1.— A three-color figure showing HST/ACS F658N (in red) and two energy bands of Chandra data (0.4 - 0.7 keV in green and 0.8 - 1.5 keV in blue). The field of view shown is 279″ × 331″, with north up and east to the left. The X-ray data have been binned by 4 pixels and smoothed with a 3-pixel Gaussian filter to remove pixelation. Note the extended region of X-rays coincident with the bulge in the Hα image. The drop-off in X-ray at upper left is due to a CCD-chip boundary and is not real.

Fig. 2.— The full field of view ACS F658N (Hα) image of the NW Balmer filament in SN 1006. Two 10″ × 20″ boxes indicate the filament tangencies discussed in detail in this paper.

Fig. 3.— Hα emissivity as a function of position behind the shock for a non-radiative shock with $n_0 = 0.25 \, \text{cm}^{-3}$, $f_{\text{neut}} = 0.1$ and $T_e/T_p = 0.05$ at the shock. This model was computed under the assumption that charge transfer is isotropic. To account for the effects described by Heng & McCray (2006) we stretched out the broad component emission by a factor of 1.5 when comparing with the observations. The scale assumes that 1″ = 3.1 × 10^{16} cm for a distance of 2.1 kpc.

Fig. 4.— Schematic diagram of the geometry of the emitting filament along the line of sight (LOS). The light line shows a large scale ripple in the shock front, and the darker curve is the result of adding a smaller scale ripple to the light line. The fading of the dark curve towards the inside of SN1006 indicates the falloff of emissivity with distance behind the shock (Figure 3). The trace in the lower right shows the Hα brightness as a function of position for lines of sight passing near the tangency to the LOS. It is obtained by integrating the Hα emissivity along each line of sight.

Fig. 5.— Comparison of observed and computed Hα spatial profiles for position 10. The shock wave is concave outward, with the assumed radius of curvature shown in each panel. The inside of the remnant is to the right. The dashed curves correspond to the pre-shock densities listed, with the lowest density giving the highest curve on the inside and the lowest on the outside. All the models have been scaled to the observed peak intensity by using the neutral fraction shown. Neutral fractions above 1 are obviously unphysical, implying that that combination of pre-shock density and radius of curvature cannot account for the observed brightness.

Fig. 6.— Same as Figure 4 for position 28.