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OPTICAL EMISSION FROM A FAST SHOCK WAVE: THE REMNANTS OF TYCHO'S SUPERNOVA AND SN 1006

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ABSTRACT

The faint optical filaments in Tycho's supernova remnant appear to be emission from a shock front moving at 5600 km s^{-1}. The intensity of the hydrogen lines, the absence of forbidden lines of heavy elements in the spectrum, and the width of the filaments are explained by a model in which a collisionless shock wave is moving into partially neutral gas. The presence of the neutral gas can be used to set an upper limit of approximately 5×10^{47} ergs to the energy in ionizing radiation emitted by a Type I supernova. The patchy neutral gas is probably part of the warm neutral component of the interstellar medium. The existing information on the remnant of SN 1006 indicates that its emission is similar in nature to that from Tycho's remnant.

Subject headings: nebulae: supernova remnants—shock waves—stars: supernovae

I. INTRODUCTION

Morphologically, the remnants of Tycho's supernova (see van den Bergh, Marscher, and Terzian 1973) and SN 1006 (van den Bergh 1976) appear to be similar, showing thin filaments of optical emission. Proper-motion studies of Tycho's remnant (van den Bergh 1971; Kamper and van den Bergh 1978) show that the strongest filament is moving at 5600 km s^{-1}, if the distance to the remnant is taken to be 6 kpc. Considering the age of the remnant, this velocity is close to that expected for the outer shock of a blast wave obeying the Sedov similarity solution for a point explosion in a uniform medium. When combined with the hard X-ray observations of Tycho's remnant, the optical data are consistent with a 3×10^{51} blast wave propagating into a medium with $n_H = 0.2$ cm^{-3} (e.g., Kirshner and Chevalier 1978). The optical filaments lie at the outer edge of a ring of radio emission (Duin and Strom 1975; Dickel *et al.* 1977), again indicating that the filaments lie at the outer shock wave of the remnant.

The optical spectra of Tycho's remnant (Kirshner and Chevalier 1978) and of the remnant of SN 1006 (Schweizer and Lasker 1978) are similar in that only hydrogen Balmer lines have been detected with certainty. The forbidden lines of heavy elements which are normally observed in galactic emission nebulae are either absent or very weak.

Models for the emission from Tycho's remnant were briefly discussed by Kirshner and Chevalier (1978). No consistent models were found, the difficulty being that if there is thermalization in a thin shock wave moving in a medium of density 0.2 cm^{-3}, the predicted surface brightness is much smaller than that observed. In this *Letter* we investigate a new model in which the high-velocity shock wave is assumed to be overtaking neutral atoms. We find that the model is able to reproduce the basic properties of the emission.

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II. EMISSION FROM A HIGH-VELOCITY SHOCK WAVE

The main assumption made here is that the supernova remnant shock wave is moving into a partially neutral interstellar medium. There is independent evidence for the existence of such a component in the interstellar medium (e.g., Field, Goldsmith, and Habing 1969).

It is important that the neutral gas be able to survive the ionizing radiation emitted by the supernova remnant. Taking the X-ray emission measures of Davison, Culhane, and Mitchell (1976) for Tycho's remnant, we find that the time required to ionize an H atom at the edge of the remnant is approximately 2.5×10^4 years. Because this is long compared with the 400 year age of the remnant, the blast wave can interact directly with neutral atoms.

The shock wave structure is expected to be as follows. There is a collisionless shock transition in which the ions are heated to a temperature of

$$\frac{3}{16}\frac{m}{k}v_s^2 ,$$

where m is the mean particle weight of the hot gas, k is Boltzmann's constant, and v_s is the shock velocity. In Tycho's remnant, the ions may be heated to about 10^9 K. The thickness of the shock transition is approximately the ion gyroradius (e.g., Friedman *et al.* 1971), or about 10^{10} cm on the assumption that the magnetic field strength is 3×10^{-6} gauss. The degree to which the electrons are heated by plasma instabilities in the shock transition is controversial. It is generally agreed that the random electron velocities achieve values at least as large as the random ion velocities (e.g., Shklovsky 1968; Zel'dovich and Shakura 1969), so that $T_e \gtrsim T_i\,(m_e/m_i)$ where the subscript e refers to electrons and the subscript i to ions. McKee (1974) has argued that plasma instabilities are capable of thermalizing the ions and electrons so that $T_e = T_i$. Thus the range of possible electron temperatures in Tycho's supernova remnant is approximately 5×10^5 to 5×10^8 K.

The neutral atoms are not affected by the sharp shock transition and they drift into the hot postshock flow. They are eventually ionized through collisions with electrons after traveling a mean distance $l \approx v_s/C_I n_e$, where C_I is the collisional ionization rate, from the position of the shock. The electron density, n_e, is approximately 4 times its preshock value. Values for C_I from Lotz (1967) show that $C_I \propto T_e^{-0.23}$ at high temperatures; we estimate that $C_I \approx 2.4 \times 10^{-8}\ T_{e7}^{-0.23}$ cm^3 s^{-1} where T_{e7} is T_e in units of 10^7 K. Applying these considerations to Tycho's remnant where $n_e = 0.8\ x$ cm^{-3} (x is the ionized fraction) and $v_s \approx 5.6 \times 10^8$ cm s^{-1}, we find $l \approx 6 \times 10^{16}\ T_{e7}^{+0.23}\ x_{0.5}^{-1}$ cm where $x_{0.5}$ is the initial ionized fraction in units of 0.5. The length l is the characteristic distance over which emission from neutral atoms is expected to occur.

Cox and Raymond (1978) have recently calculated the line emission produced during the ionization of a plasma. Their results appropriate to the supernova remnant case are shown in Tables 1 and 2, which give the number of photons produced per ionization of the parent element. In Table 1, case A refers to the assumption that the emitting region is optically thin in all H I absorption lines and case B to the assumption that the emitting region is optically thick in the Lyman lines. Over the range 10^6 K $< T_e < 10^8$ K, the values for H are constant within 5% and those for He II within 10%. The accuracy of the values is about 25% for Hα, 40%, for Hβ, and 50% for Hγ, He II λ4686, and He I λ5876. For the forbidden lines (Table 2), the maximum value assumes that the collision strength Ω is constant with energy E, and the minimum value assumes $\Omega \propto 1/E^2$. The listed values are for $T_e = 3 \times 10^7$ K. The maximum values are proportional to $T_e^{-1/2}$ and the minimum values to $T_e^{-2.5}$. The estimated values are probably within a factor of 10 of the correct values. The calculated spectrum shows that the forbidden lines are very weak compared with the H lines, as is observed in both Tycho's remnant and the remnant of SN 1006. Assuming that He is 0.1 of H by number and that case A applies, the He I λ5876 line is predicted to have a strength about 0.1 that of the Hβ line.

TABLE 1

H AND He PHOTONS PRODUCED PER IONIZATION

	Case A	Case B
Hα	0.048	0.27
Hβ	0.016	0.075
Hγ	0.0064	0.030
He II λ4686	5.6×10^{-4}	0.0015
He I λ5876	0.02	0.02

TABLE 2

FORBIDDEN-LINE PHOTONS PRODUCED PER IONIZATION

	Estimate	Minimum	Maximum
[O II] λ3727	2×10^{-4}	1.7×10^{-6}	0.028
[O III] λ5007	2×10^{-4}	1.1×10^{-6}	0.023
[N II] λ6584	5×10^{-5}	3.6×10^{-7}	0.006

Given the value of l calculated above for Tycho's remnant, case A is probably more appropriate than case B for the postshock region. However, the preshock gas can absorb Lyman photons; this increases the number of Hα photons produced per ionization. We let $\epsilon_{0.1}$ be the number of Hα photons produced per ionization in units of 0.1. The line intensity through the front of a shock wave is $\epsilon n_{\rm H}(1 - x)\ v_s h\nu/4\pi$ where ν is the frequency of the line under consideration. Taking the values appropriate to Tycho's remnant and $x = 0.5$, we find that the predicted Hα intensity is 1×10^{-6} $\epsilon_{0.1}$ ergs cm^{-2} s^{-1} sr^{-1}. The intensity is increased by the longer path length through the emitting region at the edge of the remnant. If the remnant is spherical, the intensity at the edge is increased by approximately a factor of $(R/l)^{1/2}$, where R is the radius of the remnant. For Tycho's remnant with $R = 7$ pc, the intensity may be increased by a factor of 20 at the edge. The Tycho filaments have an observed intensity somewhat greater than 1×10^{-6} ergs cm^{-2} s^{-1} sr^{-1} (Kirshner and Chevalier 1978), so that the theoretical intensity predictions agree well with the observations. At a distance of 6 kpc, $1'' = 9 \times 10^{16}$ cm, so that the length l is near the limit of resolution. This agrees with the presence of narrow filaments in Tycho's remnant.

As mentioned above, the exact amount of electron heating in the collisionless shock wave is not known and the theoretically expected values for T_e cover a large range. Unfortunately, the predicted values of H line intensities and l are not very sensitive to T_e in this temperature range, so that the actual value of T_e cannot be deduced from the observations. However, the weak forbidden-line intensities are probably sensitive to T_e, so that if they can eventually be observed and if accurate collision strengths become available, they may give information on the degree of electron thermalization in the shock wave.

The neutral atoms entering the postshock region are subject to charge exchange with the high-velocity protons. In Tycho's remnant, the proton energies are about 100 keV, so that the cross section to charge exchange $\sigma \approx 1 \times 10^{-17}$ cm^2 per atom (McClure 1966). The mean free path to charge exchange is $L = (n_p\sigma)^{-1} \approx 2.5 \times 10^{17}\ x_{0.5}^{-1}$ cm, which is about a factor of 4 larger than l, the mean free path to collisional ionization. Thus, about 20%–30% of the emission should be from high-velocity atoms, while the rest of the emission is from low-velocity gas. The observations of the Hα line in

Tycho's remnant do show a sharp emission line with faint broad wings (Kirshner and Chevalier 1978). Quantitative line profiles do not yet exist. Future theoretical and observational investigations of the emission-line profiles may yield information on the structure of the high-velocity shock wave.

III. DISCUSSION

The presence of regions of neutral gas in the vicinity of a supernova remnant has two implications. The first is that there cannot have been a burst of ionizing radiation from Tycho's supernova which completely ionized a region greater than 7 pc in radius. For an ambient density of 0.2 cm^{-3}, the recombination time is much longer than the age of Tycho's remnant. The implication is that fewer than $\frac{4}{3}\pi R^3 n_{\rm H} = 8 \times 10^{57}$ atoms were ionized by the initial supernova burst. If each ionization involves a 40 eV photon, the limit on the radiated ionizing energy is 5×10^{47} ergs. This estimate may be increased if there were dense neutral regions less than 7 pc from the site of the supernova. However, at least $8M_\odot$ of absorbing gas would be required, and it is unlikely that this mass of gas could have come from presupernova mass loss. With regard to interstellar gas, the circular symmetry of the radio emission (Duin and Strom 1975) argues against substantial interstellar inhomogeneities. The estimate may also be modified if the distance to the supernova D, is incorrect. Assuming that the total energy of the supernova is known and that the expansion obeys the Sedov similarity solution, the limit on the energy in ionizing radiation scales as D^{-2}.

The available information on Tycho's supernova indicates that it was a Type I supernova (Baade 1945). In the model for Type I supernovae by Morrison and Sartori (1969), about 10^{52} ergs of ionizing radiation are emitted at the time of the supernova. The present model clearly conflicts with the Morrison-Sartori model. However, evidence against the Morrison-Sartori model was previously found by observations of the lack of [O III] emission surrounding Tycho's remnant (Reynolds and Ogden 1978). Reynolds and Ogden set an upper limit of 1.5×10^{49} ergs to the energy in 40 eV photons. The present considerations provide further evidence that the Morrison-Sartori model for Type I supernovae is incorrect.

Hydrodynamic models of supernovae do predict ionizing bursts at the time of shock breakout, although at a level considerably below that required by the Morrison-Sartori model. One class of models for Type I supernovae involves the instantaneous deposition of energy in an extended stellar envelope (Lasher 1975). Supernova models of this type predict an ionizing burst in the range 10^{48} to 10^{49} ergs (Lasher and Chan 1975; Klein and Chevalier 1978). The energy limit set here provides weak evidence against this class of models for Type I supernovae. Models involving the explosion of a compact star with late deposition of energy predict a small amount of radiated energy at the time of shock breakout (Colgate 1974) and are consistent with the present model.

The second implication involves the nature of the interstellar medium. The observations of Tycho's remnant indicate that the shock wave is moving into partially neutral gas with a density of 0.2 cm^{-3}. If the temperature of this gas is 5000 K, p/k is 1000 $(1 + x)$ dynes cm^{-2}, which is in good agreement with other estimates of the pressure in the interstellar medium (e.g., Jura 1975), considering that Tycho's supernova occurred about 160 pc from the galactic plane. The gas is probably part of the warm neutral medium previously found by 21 cm studies of interstellar gas. Near the two observed remnants, the neutral gas appears to be in regions with dimensions of several parsecs.

In summary, the intensity, spectrum, and width of the filaments observed in Tycho's remnant can be explained by a model in which a fast collisionless shock wave is moving into a partially neutral gas. The filament in the remnant of SN 1006 is probably due to a similar mechanism. The model yields an upper limit to the burst of ionizing radiation from a Type I supernova and gives information on the warm neutral component of the interstellar medium. This mechanism may give rise to faint hydrogen emission from other supernova remnants. Taking the X-ray emission measures of Rappaport *et al.* (1974) for the Cygnus Loop, we estimate that the time required to ionize an H atom at the edge of the remnant is approximately 10^5 years. Rappaport *et al.* (1974) estimate that the age of the Cygnus Loop is 1.8×10^4 years. Some of the faint Hα features studied by Kirshner and Taylor (1976) may be due to the interaction of the fast shock wave with neutral atoms. The test of this hypothesis will be to measure the intensities of the forbidden lines from this gas. If they are very weak, it will be evidence for the model discussed here.

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REFERENCES

Baade, W. 1945, *Ap. J.*, **102**, 309.
Colgate, S. A. 1974, *Ap. J.*, **187**, 333.
Cox, D. P., and Raymond, J. C. 1978, in preparation.
Davidson, P. J. N., Culhane, J. L., and Mitchell, R. J. 1976, *Ap. J.* (*Letters*), **206**, L37.
Dickel, J. R., Wells, D. C., Gull, T. R., Willis, A. G., and van den Bergh, S. 1977, in *Supernovae*, ed. D. N. Schramm (Dordrecht: Reidel), p. 63.
Duin, R. M., and Strom, R. G. 1975, *Astr. Ap.*, **39**, 33.
Field, G. B., Goldsmith, D. W., and Habing, H. J. 1969, *Ap. J.* (*Letters*), **155**, L149.
Friedman, H. W., Linson, L. M., Patrick, R. M., and Petschek, H. E. 1971, *Ann. Rev. Fluid Mech.*, **3**, 63.
Jura, M. 1975, *Ap. J.* **197**, 581.
Kamper, K. W., and van den Bergh, S. 1978, preprint.
Kirshner, R. P., and Chevalier, R. A. 1978, *Astr. Ap.*, in press.

Kirshner, R. P., and Taylor, K. 1976, *Ap. J.* (*Letters*), **208**, L83.
Klein, R. I., and Chevalier, R. A. 1978, *Ap. J.* (*Letters*), **223**, L109.
Lasher, G. 1975. *Ap. J.*, **201**, 194.
Lasher, G., and Chan, K. L. 1975, *Bull. AAS*, **7**, 505.
Lotz, W. 1967, *Ap. J. Suppl.*, **14**, 207.
McClure, G. W. 1966, *Phys. Rev.*, **148**, 47.
McKee, C. F. 1974, *Ap. J.* **188**, 335.
Morrison, P., and Sartori, L. 1969, *Ap. J.*, **158**, 541.
Rappaport, S., Doxsey, R., Solinger, A., and Borken, R. 1974, *Ap. J.*, **194**, 329.
Reynolds, R. J., and Ogden, P. M. 1978, *Ap. J.*, **220**, 172.
Schweizer, F., and Lasker, B. W. 1978. *Ap. J.*, **226**, in press.
Shklovsky, I. S. 1968, *Supernovae* (New York: Interscience).
van den Bergh, S. 1971, *Ap. J.*, **168**, 37.
———. 1976, *Ap. J.* (*Letters*), **208**, L17.
van den Bergh, S., Marscher, A. P., and Terzian, Y. 1973, *Ap. J. Suppl.*, **26**, 19.
Zel'dovich, Ya. B., and Shakura, N. I. 1969, *Soviet Astr.—AJ*, **13**, 175.

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