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THE IONIZATION EFFECTS OF SHOCK BREAKOUT IN SN 1987A

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ABSTRACT

The epoch of shock breakout in SN 1987A was almost certainly associated with the production of a pulse of UV photons with a characteristic temperature of order 10^5 K and a duration of 2–4 hr. We propose that this pulse has the characteristics required to ionize the precursor stellar wind, temporarily ionize any nearby remnants of the red giant wind, and can ionize the surrounding interstellar medium out to distances of several parsecs for several thousand years. These effects could provide transitory free-free absorption of the synchrotron radio source and may offer an explanation of the ionized knot seen in speckle interferometry. A similar but more powerful outburst could also be responsible for the highly ionized halo seen around the SMC supernova remnant 1E 0102.2 − 7219.

Subject headings: radiation mechanisms — shock waves — stars: supernovae

I. INTRODUCTION

The possibility of a UV flash associated with a supernova event has been predicated on theoretical grounds for many years (Bottcher *et al.* 1970; McCray and Schwarz 1973; Arnett 1980). The purpose of this *Letter* is to use the very detailed early-time observations of SN 1987A to compute the characteristics of such a pulse and to estimate its effects on the surrounding medium.

II. CHARACTERISTICS OF THE SHOCK BREAKOUT

The time difference between the neutrino event (Aglietta *et al.* 1987; Bionta *et al.* 1987; Hirata *et al.* 1987) and the optical outburst (A. Jones; reported in Wampler *et al.* 1987; McNaught 1987) puts very stringent limits on the size of the precursor star. From a hydrodynamic model of the shock propagation, Shigeyama *et al.* (1987) derive;

$$t_{\rm prop}(\text{minutes}) = 13(r_0/10^{12}\ \text{cm})(M_{\rm ej}/M_\odot)^{1/2} \times (E_0/10^{51}\ \text{ergs})^{-1/2},$$

where $t_{\rm prop}$ is the time for the shock to propagate from the center to the surface of the precursor star, r_0 is the radius of the precursor, $M_{\rm ej}$ is the ejected mass, and E_0 is the explosion energy. The photometric properties of the precursor indicate a radius $r_0 \approx 3.5 \times 10^{12}$ cm while an evolutionary sequence for the precursor star (Wood and Faulkner 1987) gives a total mass at explosion of $\sim 5.4\ M_\odot$. Assuming that $\sim 1.5\ M_\odot$ is incorporated into the neutron star, when $M_{\rm ej}$ is about $3.9\ M_\odot$. The observations gives an upper bound $t_{\rm prop} < 106$–184 minutes. If we adopt this upper bound for the actual time of shock breakout, then the above equation implies that $E_0 \gtrsim 4 \times 10^{50}$ ergs.

The characteristics of the early-time photosphere can be computed in an approximate manner from the observed V magnitudes and colors. We have adopted the $(B - V)$ colors and bolometric corrections given by Carney (1980) for blackbodies and have used the $(V - R)$ and $(V - I)$ blackbody colors given by M. S. Bessell (private communication). Spectra taken within the first two days of the supernova explosion indicate a relatively featureless spectrum in the UV and visible (Sonneborn and Kirshner 1987*a*; Blanco *et al.* 1987). Thus a blackbody spectrum should be a good approximation to that of the supernova during the early time interval during which the UV flash was produced. Bolometric luminosities are obtained on the assumption that the apparent distance modulus of the supernova is 18.8, corresponding to a visual $A_v = 0.44$ and a color index $E(B - V)$ of 0.14 (Danziger *et al.* 1987; Wampler *et al.* 1987; Dopita *et al.* 1987). The radius can be derived from the luminosity using Stefan's law, provided that the atmosphere radiates as a blackbody or graybody. The principal opacity source in supernova atmospheres is electron scattering, even when the temperature is as low as 5000 K. The other opacity source is line blanketing, which is severe in the UV and blue, but becomes less important in the visible and infrared. We adopt an emission efficiency of 0.9, recognizing that this could introduce a systematic error in the photometric radii. The fit to the photometry gives the following parameters in the earliest phase, $\log(t\ \text{s}^{-1}) < 5.75$;

$$\log(L/L_\odot) = (9.98 \pm 0.27) - (0.400 \pm 0.049)\log(t)$$

$$\log(R/R_\odot) = -(1.60 \pm 0.43) + (0.936 \pm 0.078)\log(t)$$

$$\log(T_{\rm eff}) = (7.47 \pm 0.23) - (0.64 \pm 0.04)\log(t).$$

If we can assume that the shocked SN ejecta expands homologously, and that, locally, the density structure can be represented by a power law with index α, then it follows that

$$\rho(r, t) = A(r/r_0)^{-\alpha}(t/t_0)^{(\alpha - 3)},$$

where r_0 is the initial radius at the time of shock breakout, t_0. At any time, we can see down to a radius R at which the optical depth due to all opacity sources ~ 1.0; hence it follows that

$$R \propto (t/t_0)^{(\alpha-3)/(\alpha-1)}$$

The observed power-law slope of the radius-time relationship is therefore a direct measure of the density gradient in the vicinity of the photosphere. For $\log(t) < 5.75$, the bolometric luminosity declined somewhat and the velocity of expansion of the photosphere was almost constant at about 10,400 km s^{-1}, although the absorbing layers showed an initial expansion velocity which was as high as 15,000 km s^{-1} (Danziger *et al.* 1987). The fit with the photometry implies that the power law characterizing the photospheric density gradient was very steep, with α of order 30. However, the absorption-line profiles suggest a much shallower density gradient in the outermost layers. From this it appears that the photosphere of the supernova was locked close to the boundary of presupernova atmosphere, whereas the shock had accelerated into the stellar wind of the presupernova star.

The epoch of shock breakout from the photosphere certainly resulted in a "flash" of UV photons, although not a very intense one. On the basis of the timing arguments given above and the computed size of the precursor star, we can conclude that shock breakout occurred at $\log(t) \approx 3.6$, i.e., when R given by the regression equation above was equal to $r_0 = 3.5 \times 10^{12}$ cm. At this time the regressions also give a photospheric temperature, $T_{\rm eff} \approx 150{,}000$ K, and a luminosity of 3.5×10^8 $L_\odot$. This should be compared with the estimate derived on the assumption that, at the time of shock breakout, the postshock gas is radiation dominated so that

$$\rho(r_0, t_0) V_{\rm sh}^2 = a T_{\rm eff}^4 ,$$

where $V_{\rm sh}$ is the shock velocity, and a is the radiation constant. Using a precursor photospheric density of 5×10^{-11} g cm^{-3} and a shock velocity of 15,000 km s^{-1} (Danziger *et al.* 1987) gives $T_{\rm eff} \approx 350{,}000$ K. The temperature falls below 40,000 K in a time scale of 7 hr, at which point it can no longer ionize effectively. Thus the UV flash can probably be characterized by a temperature of order $(1-3) \times 10^5$ K, a luminosity of $(2-3) \times 10^8$ $L_\odot$, and a duration of 2–4 hr.

As a test of the characteristics deduced above for the supernova, we can compare the flux predicted by a our model with the first *IUE* observation (Sonneborn and Kirshner 1987*b*) which gave a flux at 1860 Å of 8.5×10^{-11} ergs cm^{-2} s^{-1} $Å^{-1}$ on 1987 February 24.98 UT ($\log t = 5.16$). From the model above, with $\log t = 5.16$, we find $T_{\rm eff} = 14{,}700$ K and $\log L/L_\odot = 7.92$. Using the blackbody approximation and adopting the LMC extinction curve in the UV given by Nandy *et al.* (1981), we predict a flux at 1860 Å of 1.3×10^{-10} ergs cm^{-2} s^{-1} $Å^{-1}$, in quite good agreement with the observed *IUE* flux.

III. PREIONIZATION OF THE BLUE SUPERGIANT WIND

The prompt radio burst is related to this early epoch of shock breakout and expansion of a compact initial configuration. The burst lasted only about a week (Turtle *et al.* 1987) and can be understood in terms of free-free absorption of shock-generated synchrotron emission (Storey and Manchester 1987). We believe that the location of this radio emission was probably in the shocked stellar wind region of the star, with the free-free absorption arising from the portion of the wind which had been ionized by the UV flash—see also Chevalier and Fransson (1987). The free-free absorption coefficient is given in terms of the frequency, ν, temperature, T, and density, n, by:

$$\kappa_\nu = 2.7 \times 10^{-20} (T/{\rm K})^{-1.35} (\nu/{\rm GHz})^{-2.1} (n/{\rm cm}^{-3})^2 .$$

For a precursor star with the effective temperature of Sk −69 202 (13,000–16,000 K), the wind expansion velocity is of order 550 km s^{-1} (Waldron 1984), and the mass-loss rate immediately prior to the explosion is $\sim 6 \times 10^{-6}$ $M_\odot$ yr^{-1}. This mass-loss rate is 2.5 times the rate given by the formulae of Waldron (1984), and it gives a reasonable ratio of red to blue supergiants in the LMC while at the same time bringing the precursor star back into the blue region of the H-R diagram at the time of supernova explosion (Wood and Faulkner 1987). The density in the wind is therefore of order

$$(n/{\rm cm}^{-3}) \approx 2.5 \times 10^5 (r/10^{15}\ {\rm cm})^{-2} .$$

Note that the effective temperature of the precursor star is too low to effectively ionize the wind. However, the UV pulse will easily ionize this wind, and the recombination time scale (approximately $[n/10^8\ {\rm cm}^{-3}]^{-1}$ days) is long for distances greater than about 10^{14} cm out in the wind. Using the opacity equation above, optical depth unity in free-free scattering will occur at about 10^{15} cm out in the wind. The observed transition between optically thick and the optically thin radio emission occurred about 4 days after the supernova event. The blast wave would therefore have to have a velocity of 29,000 km s^{-1} in order to emerge from its electron scattering cocoon in this time scale, with the assumed wind parameters. This is in very good agreement with the greatest absorption velocities seen in the Hα P Cygni profile at early times, about 25,000 km s^{-1} (e.g., Danziger *et al.* 1987). We can therefore conclude that the observations of the development of the radio pulse are consistent with the hypothesis that the free-free absorption arises from a photoionized stellar wind.

IV. IONIZATION OF A REMNANT OF THE RED SUPERGIANT WIND

The discovery by speckle interferometry of a bright line-emitting knot at a distance of 0".057 from the supernova (Karovska *et al.* 1987; Marcher, Meikle, and Morgan 1987) suggests that a blob of circumstellar gas became ionized on about March 23. This blob of gas could be a remnant of the wind produced in the red supergiant phase of evolution, or perhaps some ejecta from a more recent evolutionary phase as the precursor star evolved back to the blue. The speckle results place the ionized blob at ~ 0.01 pc, which implies an age of 300–1000 yr if we assume the blob has an expansion velocity of $\sim 10-30$ km s^{-1} typical of a red supergiant wind. However, since the star takes about 5000 yr to evolve from red to blue in the H-R diagram (Wood and Faulkner 1987), it would appear that the blob of gas came from some more recent ejection event or, alternatively, that the gas in the blob has a very small expansion velocity. Perhaps the simplest explanation of the origin of the blob is that it represents part of a dense, equatorial ring of matter ejected during the red giant phase. This type of geometry has been associated with bipolar nebulae and OH/IR sources in our Galaxy (for example, OH 0739−14; Cohen *et al.* 1985).

We assume here that the gas in the blob has been compressed by the ram pressure exerted on it by the hot stellar wind coming from the precursor star. If we adopt a temperature of 100 K for the gas in the blob, then the characteristic

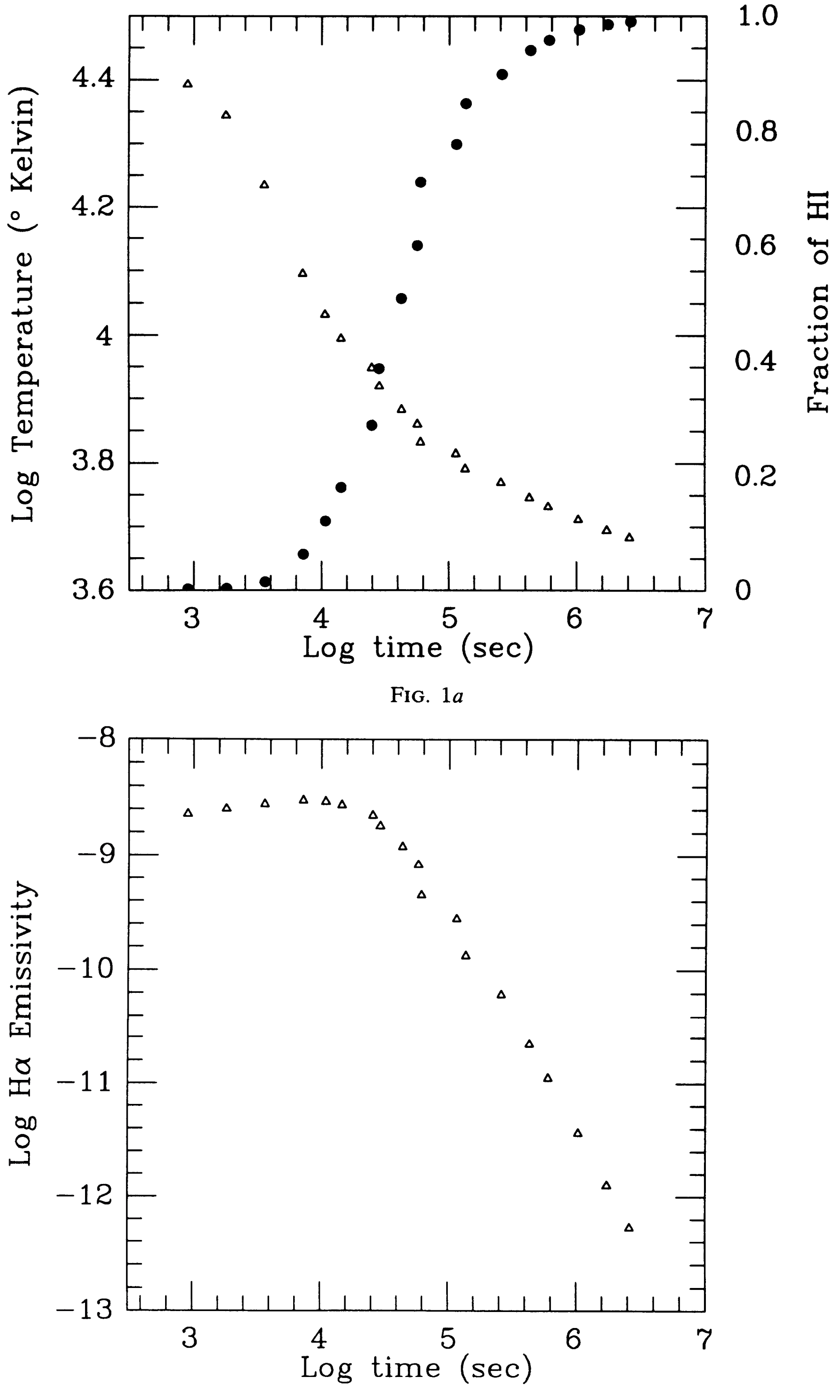

FIG. 1*a*

FIG. 1*b*

FIG. 1.—(*a*) The temperature and ionization history and (*b*) the Hα emissivity of a blob of gas with density 10^8 cm^{-3}, illuminated by a UV flash with the characteristics described in the text, diluted by a factor of 10^8. These conditions should be representative of the blob of material seen in the speckle interferometric measurements of SN 1987A.

density is 10^8 cm^{-3}. We have computed the time-dependent temperature and ionization history of such a blob using the generalized spectral modelling code MAPPINGS (Binette 1982; Binette, Dopita, and Tuohy 1985), noting that the radiation field from the supernova is diluted by a factor of 10^8. The results are shown in Figure 1. The initial ionization is extremely rapid, taking only a few minutes, and so the resultant spectrum is determined entirely by the cooling and recombination phase. The recombination time scale is $\sim (n/10^8 \text{ cm}^{-3})^{-1}$ days, and so recombination is complete in a few days. The density of the blob is sufficiently high to suppress forbidden-line emission except for the [O I] lines, which appear weakly. The emission spectrum is therefore dominated by the recombination lines of hydrogen and helium, both of which appeared to be present in the observations (Marcher, Meikle, and Morgan 1987). The emissivity of Hα is also shown in Figure 1. The ionization parameter is about 3×10^{11} photons atom^{-1} cm s^{-1}. Since the burst duration is $\sim 10^4$ s, a column approximately 0.0010 pc can be ionized before the UV photons are depleted. The ionized zone is therefore thin in comparison to its distance from the supernova.

The blob would have to be spatially extended, in apparent disagreement with the speckle results which indicate a small size for the emitting knot. The recombination time scale is only 1 day, but it was seen at an almost constant magnitude over at least 20 days. It therefore had to be larger than 0.02 pc in radial extent. It would also have to be optically thick to the UV flash and cover an appreciable angle as seen from the supernova in order to satisfy the energy requirements of a fluorescent source. The reported magnitude (Karovska *et al.* 1987) is equivalent to 6.2 in a 10 nm bandpass at Hα. This is equivalent to 2.3×10^{38} ergs s^{-1} in the Hα line, or at least 4×10^{44} ergs in total. However, the total UV energy associated with the photon burst is only of order 10^{46} ergs. Since the cooling in Hα is only about 10% of the total, a large fraction of the energy of the total UV pulse would have to be absorbed and reemitted over 20 days. These requirements would become only slightly less stringent if some of the optical emission resulted from dust scattering of the optical photons produced by the supernova.

The dense equatorial ring of gas suggested above is one possible way of providing the type of geometry needed to absorb a large fraction of the UV flash, although this is at variance with the small size of the blob seen in the speckle results. Alternatively, for a small emitting blob, the UV flash would need to be 1 or 2 magnitudes larger than predicted here. In addition to the above problems, it is difficult to see how excitation by a UV flash could explain the speckle observation of a blob in emission at 5330 Å.

V. PRODUCTION OF A FOSSIL STRÖMGREN SPHERE

Given the very high luminosity of the UV flash, it is reasonable to ask whether it could be responsible for generating a fossil Strömgren sphere in the interstellar material. With the parameters of the flash computed above, and assuming no absorption, the ionization parameter, Q, at the inner edge of the sphere is

$$(Q/\text{cm s}^{-1}) = 2 \times 10^{15}(r/\text{pc})^{-2}(n_{\text{H}}/\text{cm}^{-3}).$$

This implies that the ionization front is enormously supersonic. The duration of the burst is what determines the thickness of the ionized zone produced by this flash. Assuming 10^4 s, the thickness, Δr, of the ionized zone is therefore given by;

$$(\Delta r/\text{pc})^3 \approx 7(n_{\text{H}}/\text{cm}^{-3})^{-1}.$$

The pulse of UV photons from SN 1987A is therefore only capable of ionizing a regin of 2–4 pc across, according to whether the interstellar medium has a density of 1 or 0.1 cm^{-3}.

Only one example of a highly ionized shell is known to be associated with a supernova remnant, the case of the oxygen-rich remnant 1E 0102.2 − 7219 in the SMC (Tuohy and Dopita 1983). In this case, the ionized shell is about 15 pc in radius. This implies that the photon burst would have to be 50–500 times more powerful than that produced in the case of SN 1987A. A "normal" Type II supernova could easily produce such a photon burst, provided that the color temperature of the pulse is similar to that of SN 1987A: for a "normal" Type II event, the precursor star is a red supergiant, and it will have a much larger surface producing the UV flux.

The observed spectrum of 1E 0102.2 − 7219 can be plausibly explained on the hypothesis that it is a fossil Strömgren sphere. The initial ionization and heating by the "normal" Type II burst described above is very rapid so, again, the spectrum at any time is determined by the cooling and recombination that has occurred since the event. With a density of order 1–3 cm^{-3}, the recombination and cooling time scales are sufficiently long to ensure that spectra with the observed characteristics ($T_e \approx 15{,}000$ K, [O III] λ5007 Å ≫ Hβ, [O II] λ3727,9 Å ≫ Hβ, He II λ4686 Å ≈ 0.5 Hβ) can be generated by the plasma about 1000 yr after the supernova event.

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