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MYSTERY SPOT IN SUPERNOVA 1987A: REFLECTION OR FLUORESCENCE BY AN INTERSTELLAR CLOUD?

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ABSTRACT

We explore fluorescence and reflection models of the companion to SN 1987A observed by speckle interferometry, recalling a 1901 precedent. The apparent small angular size of the companion is a severe constraint. A fluorescence model cannot reach the observed brightness unless the ultraviolet burst from the supernova contained as many as 2×10^{58} ionizing photons. This is $\sim$25 times stronger than generous current models. Even then the expected line ratios and widths do not fit the observations. The absence of narrow Hα and Hβ lines in the supernova spectrum, the ratio of fluxes of the companion in Hα and [N II] filters, the invisibility of the companion at λ4861 (Hβ), and its detection at λ5330 fail to agree with theory. A dust-reflection model is more promising, and the color can be reddened by the evaporation of small grains, but the model still falls $\gtrsim$1 mag short in brightness. Furthermore, a dust reflection should have increased in relative brightness in 1987 May–June, rather than disappearing as the mystery spot did. If all the observations are correct, neither model is likely to work.

Subject headings: nebulae: H II regions — nebulae: reflection — stars: individual (SN 1987A) — stars: supernovae

I. INTRODUCTION AND GENERAL CONSIDERATIONS

The "mystery spot" or bright "companion" to Supernova 1987A in the Large Magellanic Cloud observed by speckle interferometry from March 25 through April 14 poses a challenge to theorists. Table 1 summarizes the observations as inferred from published reports. Early optical observations of the spot were positive and showed a projected separation of about 0".06. Later optical observations at many wavelengths in the period May 30–June 2, and again on November 15, not yet reported fully and therefore not listed in detail in Table 1, were negative and implied $\Delta m > 4$ (May–June) and $\Delta m > 4.5$ (November 15).

Early infrared speckle observations (May 9) were negative at the 5% level. Later observations (June 7–22 and August 6) were negative until June 16 and then began to show some kind of companion structure (Chalabaev, Perrier, and Mariotti 1988*b*), which the authors interpret as a clumpy dust echo. Nevertheless the authors interpret all these infrared results as negative with respect to the mystery spot, because they were negative during the early period, closest to the time when the optical spot was detected. Tentatively we show them all in Table 1 as negative at the 5% level. We note that in the recent paper cited, the infrared observers to some extent contradict their earlier analysis, and also that they derive an upper limit on the strength of the UV-visible burst by the supernova ($< 4 \times 10^{42}$ ergs s^{-1}), which is inconsistent with the expected strength of the burst in popular models (Woosley, Pinto, and Ensman 1988). We await a more detailed report on these IR data.

One obvious possibility for a model is "echo" reflection and/or fluorescence by a circumstellar or interstellar cloud. Dopita *et al.* (1987) and Hillebrandt *et al.* (1987) have put forth rudimentary models of this sort, emphasizing fluorescence rather than reflection; Meikle, Matcher, and Morgan (1987) and Phinney (1987, 1988) also mention such a model and call attention to its problems. Schaefer (1987) and Chevalier (1987) rightly emphasize a remarkable but almost forgotten precedent for an echo: the "superluminally expanding" nebulosity around Nova Persei 1901 (Couderc 1939; Ritchey 1902; Perrine 1902, 1903; Felten 1988; Katz and Jackson 1988), which created a sensation akin to the present one. Although ambiguities of interpretation remain (Payne-Gaposchkin 1957), this was surely a reflection nebula (Couderc 1939; Kapteyn 1901). Large arc-shaped echoes, similar to those of 1901, have now been detected around SN 1987A (Crotts 1988; Rosa 1988; Heathcote and Suntzeff 1988; Suntzeff *et al.* 1988). Nisenson *et al.* (1987) and Meikle, Matcher, and Morgan (1987) raise briefly the possibility of a reflection model for the mystery spot but dismiss it because of the high brightness required. In unpublished work, Phinney (1987, 1988) was unable to devise a successful model. We have considered models of both types, and, while our conclusions are not optimistic, we think it worthwhile to explore the theoretical opportunities and the observational difficulties more thoroughly than earlier authors. We invite colleagues to examine our calculations and seek ways in which the strictures could be evaded. Reflection and fluorescence echoes have also been discussed very recently in the context of luminous arcs in clusters of galaxies (Katz 1987; Milgrom 1987; Katz and Jackson 1988; Braun and Milgrom 1989).

The projected separation l between supernova and "reflector" (Fig. 1) is determined by the angular separation, 0".06. At $D = 55$ kpc, we have $l \approx 4.9 \times 10^{16}$ cm ≈ 3300

TABLE 1

OBSERVATIONS OF THE MYSTERY SPOT IN SN 1987A

Dates (1987)	Filter Center	Filter Width	Magnitude Difference (companion *minus* SN)	Reference
Mar 25	6560 Å	100 Å	2.7 ± 0.2	1, 2
Apr 2	6560 Å	100 Å	2.7 ± 0.2	1, 2
	5330 Å	100 Å	3.0 ± 0.2	2
	4861 Å	16 Å	>4	3
	4500 Å	100 Å	3.5–4.0	1, 2
	4000 Å	100 Å	>4	2
	3869 Å	15 Å	>4	3
Apr 11	4921 Å	15 Å	>4	3
	4861 Å	16 Å	>4	3
Apr 14	6585 Å	10 Å	~ 3	3
	5876 Å	10 Å	>4	3
May 9	4.6 μm	≈ 1 μm	>3.2	4, 5
	3.8 μm	≈ 1 μm	>3.2	4, 5
	2.2 μm	≈ 1 μm	>3.2	4, 5
May 30–Jun 2	See text		>4	6
Jun 7–22	4.6 μm	≈ 1 μm	>3.2	4, 5
	3.8 μm	≈ 1 μm	>3.2	4, 5
	2.2 μm	≈ 1 μm	>3.2	4, 5
Aug 6	4.6 μm	≈ 1 μm	>3.2	5, 7
	3.8 μm	≈ 1 μm	>3.2	5, 7
	2.2 μm	≈ 1 μm	>3.2	5, 7
Oct 25	6560 Å	90 Å	>4	8
	5890 Å	100 Å	>4	8
	4860 Å	100 Å	>4	8
Nov 15	See text		>4.5	9
Nov 25	6560 Å	90 Å	>4	8
	5890 Å	100 Å	>4	8
	4860 Å	100 Å	>4	8

REFERENCES.—(1) Nisenson *et al.* 1987. (2) Papaliolios *et al.* 1988. (3) Meikle, Matcher, and Morgan 1987. (4) Perrier *et al.* 1987. (5) Chalabaev, Perrier, and Mariotti 1988*b*. (6) Karovska *et al.* 1987. (7) Chalabaev, Perrier, and Mariotti 1988*a*. (8) Matcher *et al.* 1988. (9) Karovska 1988.

AU $\approx$ 19 light-days. We do not know where along the line of sight the reflector lies. If the line from the supernova (SN) to a point reflector makes an angle θ with the line from SN to observer, and the SN-to-reflector signal travels at speed βc, the true separation is l csc θ, and the geometric delay time in a reflected signal is

$$t_d = lc^{-1}(\beta^{-1} \csc \theta - \cot \theta) . \tag{1}$$

We have $t_d \gtrsim l(\beta c)^{-1}$ unless $\beta \approx 1$ *and* $\theta \ll \pi/2$. The echo was first seen after a delay of 30 days and may have appeared earlier. Since $l/c \approx 19$ days, the blast wave, which travels at only $\beta \leq 0.1$, cannot have carried this signal. We explore the possibility of radiation or relativistic particles: $\beta = 1$. We can reject values of θ large enough to make $t_d > 30$ days, i.e., we reject $\theta > 115°$ approximately. Small θ is allowed; for $\theta \ll \pi/2$ we have $t_d \approx l\theta/2c$. The delay time has no minimum and is uncertain by 30 days. We should remember this when comparing the echo with the SN. If the reflecting cloud has a diameter $2r \ll l$, then, barring a bizarre shape (specifically, a section of a thin paraboloidal sheet with SN at focus and observer on axis) and assuming a roughly symmetrical cloud, we find that there is a total spread in delay times

$$\Delta t_d \approx 4rl^{-1}t_d(1 + c^2t_d^2/l^2)^{-1/2} , \tag{2}$$

which is $\sim(2\text{–}4)rt_d/l$ for $2\pi/3 \geq \theta \geq 0$.

It is not ostensibly helpful to place the reflector at small θ (i.e., in the foreground). Its distance from the SN increases, which increases the difficulty of accounting for the high intensity of the scattered radiation. As regards dust reflection, this

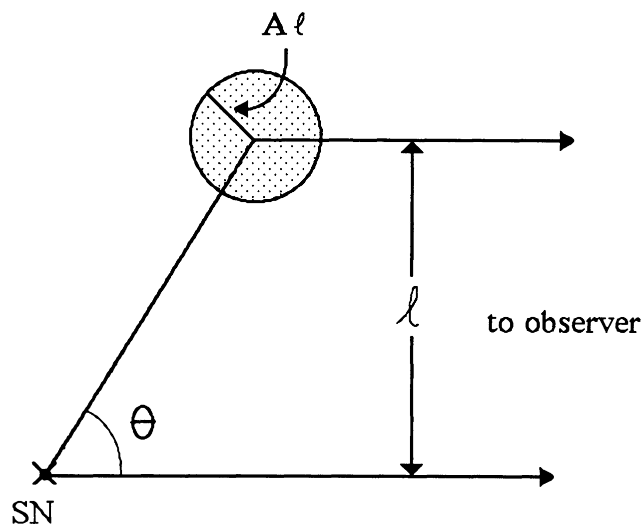

FIG. 1.—Simple spherical model of a fluorescing or reflecting cloud

drop-off in brightness may be canceled partially by the forward-throwing phase function of dust (Witt *et al.* 1982; Savage and Mathis 1979) if the optical thickness for extinction, τ_e, is less than unity. For $\tau_e \gg 1$, on the other hand, shadowing could further reduce the brightness of the reflector if θ is small, for then we are looking at the back side.

For rough calculations we place the center of the reflector (Fig. 1) at $\theta = \pi/2$, so that l is the true distance to the center. We assume that the reflector was initially a uniform sphere of gas (and possibly dust) with radius $r = Al$. Observations (Nisenson *et al.* 1987; Meikle, Matcher, and Morgan 1987) constrain A, ostensibly, to be less than unity. A limit $A < 0.27$ has been given (Meikle, Matcher, and Morgan 1987). We will carry A as a parameter, with the intention of setting it as high as $\frac{1}{2}$; we will show that $A = 0.27$ is hardly sufficient.

II. A FLUORESCENCE MODEL

Although, as we will show, there are difficulties with a fluorescence theory of the echo, we explore this possibility first, because it has been raised seriously in two earlier papers. Dust may interfere with a fluorescence model, so for the moment. We assume its absence. The postulated cloud, when confronted by the SN, will suffer ionization, which may or may not extend throughout the cloud. To build a successful model, we should adjust the size and density of the cloud so as to intercept as many ionizing photons as possible and then reradiate the energy as recombination line photons. The recombination must not be too slow, but the duration of radiation at the observer must be at least several weeks. We need to account for the large observed luminosity (Nisenson *et al.* 1987) around $\lambda 6563$ (Hα). Then we need to check whether the expected luminosities in Hβ and other lines agree with all the observations in other filters.

We discuss this in a simple quasi-Strömgren approximation (Schwarz 1973). Most of the ionization will be produced by the ultraviolet burst which emerges within a few hours after core collapse. For rough calculations, S. E. Woosley (1987) has given us a light curve and temperature history for the UV burst in a recent model (model TWOBF10) devised to fit SN 1987A. This burst emerges ≈ 100 min after core collapse, lasts ≈ 7 hr, and has a peak luminosity $L \approx 3.4 \times 10^{43}$ ergs s^{-1} and peak color temperature $T_b(\max) \approx 2.3 \times 10^5$ K. A rough integration shows that this burst contains total photon energy $E_{\rm UV} \approx 7 \times 10^{46}$ ergs, including $N \approx 8 \times 10^{56}$ ionizing photons (above the Lyman limit), which contain $E_{\rm Lyc} \approx 4 \times 10^{46}$ ergs, or more than half the energy. The TWOBF10 UV burst is essentially equal (Woosley 1989) to that which occurs in the recently popular model 10H (Woosley 1988). At these early times the mixed model 10HMM (Pinto, Woosley, and Ensman 1988), currently favored, would also give an equal result. For comparison, model 15B of Woosley, Pinto, and Ensman (1988) has $N \approx 4 \times 10^{56}$ and $E_{\rm Lyc} \approx 2 \times 10^{46}$ ergs, and the burst assumed by Dopita *et al.* (1987) apparently has $N \sim (1\text{–}2) \times 10^{56}$, so our burst is quite generous. This TWOBF10 burst contains as many ionizing photons as 6 weeks of the postflash optical radiation assumed by Raga (1987). The true optical light curve after the flash is even less effective at ionization than Raga's model, because he assumed a temperature $T = 4 \times 10^4$ K—much too high.

Because the ionization is impulsive and rapid, the condition determining the radius of the H II region is different from the usual Strömgren sphere condition; the recombination coefficient does not appear. The spherical shell of ionizing photons sweeps outward at speed c and ionizes the hydrogen until the N photons are exhausted. If the number density of hydrogen in the cloud is n, the condition

$$nAl > N/4\pi l^2 \tag{3}$$

will ensure that the cloud remains optically thick above the Lyman limit and absorbs all incident ionizing photons. This is favorable to a large fluorescent luminosity. The ionization front then penetrates a distance $X = N/4\pi l^2 n$ into the cloud, while the back side remains essentially neutral. If the recombination time t_r is $\gg X/c$, then X is also the thickness of the H II layer; if $t_r \ll X/c$, a recombination front follows the ionization front at speed c, and the thickness is $\sim ct_r$. The density required by inequality (3) for $N \sim 8 \times 10^{56}$ is

$$n > 5 \times 10^5/A \text{ cm}^{-3} , \tag{4}$$

which is $> 10^6$ cm^{-3} for acceptable values of A ($\leq \frac{1}{2}$). The recombination time t_r in the H II region at temperature $T_{\rm II}$ is (Osterbrock 1974, § 2.2)

$$t_r \sim (1 \times 10^5/n)(T_{\rm II}/10^4 \text{ K})^{1/2} \text{ yr} . \tag{5}$$

We assume a "case B" nebula, optically thick in Lyman lines (Osterbrock 1974, §§ 2.3, 4.2), and we expect the true situation in the cloud to be close to this. How high is $T_{\rm II}$? The ionization state of helium in the H II region after the burst requires a careful time-dependent computation, but we believe (Schwarz 1973; Kafatos 1973) it will be mostly He II, because most of the hydrogen-ionizing photons come during the later part of the burst when $T_b < 10^5$ K. If helium is present at cosmic abundance (Spitzer 1978, p. 4) $n/n_{\rm He} \approx 10$ and goes mostly into He II, then, allowing for ionization potentials, we may estimate $T_{\rm II}$ immediately after the burst from

$$\frac{E_{\rm Lyc}}{N} \approx \frac{10}{11}\left(2 \times \frac{3}{2} kT_{\rm II} + 13.6 \text{ eV}\right) + \frac{1}{11}\left(2 \times \frac{3}{2} kT_{\rm II} + 24.6 \text{ eV}\right) . \tag{6}$$

For the TWOBF10 burst, this gives $T_{\rm II} \approx 6 \times 10^4$ K. Cooling from this temperature, however, will be rapid. The usual cooling parameter (Dalgarno and McCray 1972) Λ/n^2 is $\gtrsim 10^{-22}$ ergs cm^3 s^{-1} for $T_{\rm II} > 10^4$ K. This cooling will be reduced somewhat by the high fossil state of radiative ionization, but inspection of calculations in similar cases (Kafatos 1973; Shapiro and Moore 1976; Dopita *et al.* 1987) indicates that the plasma will nevertheless cool rapidly to $\sim 10^4$ K, where the cooling time will increase and become comparable to the recombination time in equation (5). (Cooling below 10^4 K, being mostly in forbidden lines, will be reduced [Osterbrock 1974, §§ 3.5, 3.7] by the density $n \gtrsim 10^6$ cm^{-3}.) Considering the spread in geometric delay times, it is possible that some high-temperature gas will be observed (cooling mainly through permitted lines in the UV, which reradiate most of the energy $E_{\rm Lyc}$), but most gas observed will be at $T_{\rm II} \approx 10^4$ K.

We wish to estimate the flux F of the hypothetical fluorescent cloud in various filters (Hα first of all) compared with that of the SN. The total Hα emission by the cloud is, approximately, the product of three factors: the emissivity, the total volume which becomes ionized, and the recombination time. This energy arrives at the observer over a time interval roughly $t_r + \Delta t_d$. The cloud subtends at the SN (if $\theta = \pi/2$) a fractional solid angle $\Omega/4\pi = \frac{1}{2}[1 - (1 - A^2)^{1/2}]$, or $\Omega/4\pi \approx A^2/4$ if

$A \ll 1$. The depth reached by the ionization is X. Then, allowing for helium,

$$F_{\mathrm{H}\alpha} \approx \left(\frac{h\nu_{\mathrm{H}\alpha}\alpha_{\mathrm{H}\alpha}(1.1)n^2}{4\pi D^2}\right)\left(\frac{\pi A^2 l^2 N}{4\pi l^2(1.1)n}\right)\left(\frac{t_r}{t_r + \Delta t_d}\right), \quad (7)$$

where $\alpha_{\mathrm{H}\alpha}$ is the "effective recombination coefficient," and we have assumed inequality (3). The 1.1, due to helium, drops out. For the largest plausible cloud ($A \approx \frac{1}{2}$), we find $\Delta t_d \approx 2Al/c \approx 19$ days. Putting $T \approx 10^4$ K in equation (5), we have $t_r \sim \Delta t_d$, provided that $n \sim 2 \times 10^6$ cm^{-3}. Note that $t_r \propto 1/n$, and consider F as a function of n as we reduce n for fixed A, N, and T_{II}. For $n < 2 \times 10^6$ cm^{-3}, we approach the limit $t_r \gg \Delta t_d$, in which the last factor of equation (7) becomes unity, leaving $F \propto n$. In fact F drops even faster for $n < 10^6$ cm^{-3}, because inequality (3) fails as ionizing photons start to pass all the way through the cloud. For any $n > 10^6$ cm^{-3}, we evidently get a rough approximation to F by taking the *opposite* (high-density) limit $t_r \ll \Delta t_d$. From Osterbrock's (1974) Table 4.4, $\alpha_{\mathrm{H}\alpha} \approx 1.16 \times 10^{-13}$ cm^3 s^{-1} when $T \approx 10^4$ K and $n \approx 10^6$ cm^{-3}. We put $D = 55$ kpc and reduce $F_{\mathrm{H}\alpha}$ by 0.4 mag for red extinction (Woosley *et al.* 1987). Using equations (5) and (7) and taking the high-density limit, we find

$$F_{\mathrm{H}\alpha} \approx 1.6 \times 10^{-11} A(N/10^{56}) \text{ ergs cm}^{-2}\text{ s}^{-1} \quad (t_r \ll \Delta t_d) \quad (8)$$

for the predicted flux of the spot. It is independent of n in this limit. We have purchased a high F by setting n high enough to reduce the duration of the spot to something near its kinematical minimum $\Delta t_d \sim 2Al/c < 19$ days. A small size and high F require a short lifetime, in agreement with observations so far. This is physically correct. If $t_r \ll \Delta t_d$, then the emission observed at a given time comes from a thin paraboloidal section of the cloud, with the appropriate narrow range of t_d (Couderc 1939; Dwek 1983; Milgrom 1987). This paraboloid moves rapidly through the cloud, so motion of the source on the plane of the sky might be expected. Observations do not rule out and may suggest some motion. Motion could be minimized in a special geometry, e.g., a sausage-shaped cloud pointed nearly along the line of sight. If the density is lower and $t_r \sim \Delta t_d$, motion again is minimized, and F drops a bit below the high-density limit of equation (8).

We have said nothing yet about the nature or origin of such a cloud. For the moment we have no need to set n much higher than a few times 10^6 cm^{-3}; F is independent of n at high n. Dopita *et al.* (1987) suggest that the cloud is some kind of remnant ejecta from the former red giant, shocked and compressed by the fast wind from the blue supergiant. They assume $T = 100$ K *after compression* and derive $n = 10^8$ cm^{-3} by an unspecified ram-pressure argument. Since this choice of T is arbitrary, the resulting n is also arbitrary, and probably too high for a shocked wind (cf. Chevalier and Imamura 1983; Chevalier 1987, 1988). Hillebrandt *et al.* (1987) suggest a protostellar cloud. We will return to this possibility.

We proceed to compare equation (8) with F for the SN itself. The integrated red magnitude around April 1 was (Blanco *et al.* 1987) $m_R \approx 3.1$, which is (Allen 1973) $F_\nu \approx 163$ Jy at $\lambda 7000$. The SN itself has a broad and strong Hα line (Danziger *et al.* 1987), changing rapidly. Spectrophotometry (Blanco *et al.* 1987) around April 1 showed F_ν around $\lambda 6563$ to be ≈ 0.7 mag brighter than its mean over the red band. Therefore we set the integrated $F_\nu(\lambda 6563)$ equal to 311 Jy. This necessarily includes SN plus companion. Then, with $A = \frac{1}{2}$, assuming $N \approx 8 \times 10^{56}$ (model TWOBF10) for the burst and using equation (8) for the companion, we find the magnitude difference between cloud and SN in a passband $\Delta\lambda = 100$ Å at $\lambda 6563$ to be $\Delta m \approx 6.2$ for $n > 10^6$ cm^{-3}. Thus the postulated cloud is ~ 3.5 mag fainter than the observed $\Delta m \approx 2.7$ (Nisenson *et al.* 1987).

We could increase the expected brightness of the cloud by assuming a UV burst stronger than TWOBF10 and other current models. This was the approach of Hillebrandt *et al.* (1987), who effectively set $N \sim 10^{59}$. Such a burst would be more appropriate to other supernovae (Klein and Chevalier 1978; Falk 1978) than to SN 1987A, which occurred in a star of smaller radius (Woosley, Pinto, and Ensman 1988; Fransson *et al.* 1989). There were no UV observations of SN 1987A for 35 hr after core collapse, so it is tenable to keep N as a free parameter in equation (8), though very high values can be ruled out (Fransson *et al.* 1987). To account for $\Delta m \approx 2.7$ in $\Delta\lambda = 100$ Å at $\theta \approx \pi/2$, keeping $A = \frac{1}{2}$ and assuming $n > N/4\pi A l^3$ to capture all the ionizing photons, we would need $N \approx 2 \times 10^{58}$—25 times stronger than the model TWOBF10 burst. This would drive n up to at least 3×10^7 cm^{-3}, and the recombination time down to ~ 1 day.

Could such a high-N model match observations of the spot in other bands? The speckle object was seen (Meikle, Matcher, and Morgan 1987) with $\Delta\lambda = 10$ Å at $\lambda 6585$. This is an [N II] line filter, not an Hα filter, and it is not likely that much of the Hα *from the cloud* would acquire redshift $\approx 10^3$ km s^{-1} and enter it. The usual forbidden [N II] $\lambda 6583$ will be suppressed by a factor (McCall 1984*a*) $\sim n/(10^5$ cm$^{-3})$ at the high density in the cloud. If we set $N \sim 2 \times 10^{58}$ and $n \sim 3 \times 10^7$ cm^{-3}, so that we *can* account for the Hα brightness, then we can estimate, in the same way as above, the brightness of [N II] in the cloud relative to the SN at $\lambda 6585$ with $\Delta\lambda = 10$ Å. Assuming (Spitzer 1978) that $n/n_N \approx 10^4$, and that most of the nitrogen is N II, and using the $2 \rightarrow 1$ emissivity of McCall (1984*a*) multiplied (Osterbrock 1974, Table 3.8) by $\frac{3}{4}$, we find $\Delta m \approx 6.2$ in this filter. The observed Δm (Meikle, Matcher, and Morgan 1987) is ~ 3, which disagrees with 6.2. In a fluorescence model, observations in these two filters yield an [N II]/Hα ratio, which can serve as a rough density diagnostic. The observed ratio is fairly high and suggests $n \sim 10^6$ (not 3×10^7) cm^{-3}. But if we set the density as low as 10^6 cm^{-3}, most of the ionizing photons in a burst $N \sim 2 \times 10^{58}$ will pass right through the cloud, and the absolute intensities in both Hα and [N II] will fall below the observations. Thus the data do not agree with the model.

Introducing an oblong cloud helps only a bit with this. An *infinite* cylinder along the line of sight, with radius Al, occupies at the SN (for $A \ll 1$) a solid angle $\Omega/4\pi \approx A/\pi$, compared with $A^2/4$ for the sphere. Therefore, for (maximum) $A = \frac{1}{2}$, we gain only ~ 1 mag by absorbing more photons with the cylinder. Our shortfall at Hα, for the TWOBF10 burst, was ~ 3.5 mag.

Because analysis of some of the data is still tentative, we will not stop here but will point out some other problems with a fluorescence model. We can "predict" the strength of Hβ ($\lambda 4861$) for $N = 2 \times 10^{58}$ and $n = 3 \times 10^7$ cm^{-3}, a model which matches the Hα observations. The integrated SN spectrum (Blanco *et al.* 1987) actually has an absorption trough around $\lambda 4861$. In a filter (Meikle, Matcher, and Morgan 1987) with $\Delta\lambda = 16$ Å at $\lambda 4861$ we should have $\Delta m \approx -0.9$ or even brighter; i.e., the expected fluorescent flux exceeds the SN flux! The observation in this filter is negative, implying $\Delta m > 4$. This weakness of Hβ is a stumbling block for any fluorescence model.

The published spectrophotometry (Blanco *et al.* 1987), with resolution ~ 5 Å, does not allow the presence of narrow lines at Hα and Hβ with equivalent widths >10 Å, as implied by the model above. We emphasize that narrow lines with rather small redshift would be expected from our cloud models. In the model which matches the Hα observation, the cloud radius is $r \sim l/2$ and the density is 3×10^7 cm^{-3}, giving a cloud mass $\sim 2\ M_\odot$. These properties call to mind a protostar or Bok globule (Hillebrandt *et al.* 1987; Bok, Cordwell, and Cromwell 1971; Frerking, Langer, and Wilson 1987). It is not completely unreasonable that such a protostellar or circumstellar cloud coud exist at a distance $\approx$3300 AU from a blue supergiant, but it is hard to see how it could acquire a large redshift or velocity dispersion. The heliocentric recession of the LMC is only 270 km s^{-1}, or 6 Å at λ6563, and systematic internal velocities are much smaller (Freeman 1984; Mathewson and Ford 1984). The orbital velocity at 3300 AU from a star of mass 20 $M_\odot$ is only ~ 2 km s^{-1}. The impulse striking the cloud in the ionizing photons from a strong UV burst with $N \approx 2 \times 10^{58}$ is only $\sim 1 \times 10^{-2}\ M_\odot$ km s^{-1}. Radiation pressure from the subsequent SN and from the earlier blue supergiant is also negligible. Interaction with a stellar wind is a possibility (Dopita *et al.* 1987; Chevalier and Fransson 1987) but appears too slow to affect such a massive cloud. As for line broadening, the thermal width of hydrogen lines at $T_{\rm II} \approx 10^4$ K is only ~ 9 km s^{-1}, but the thermal width of Thomson scattering is ~ 400 km s^{-1}. This could be significant, particularly for moving some Hα into the [N II] filter. Thomson scattering might not be completely negligible if N is as large as 2×10^{58}, because such a burst ionizes a column to depth X, giving optical thickness $\tau_{\rm T} = n\sigma_{\rm T} X = \sigma_{\rm T} N/4\pi l^2 \approx 0.44$, independent of n. This holds provided that nAl is large enough to satisfy inequality (3). However, $ct_r < X$ if $N > 10^{58}$, so the column ionized *at any one time* is not this deep; behind the recombination front, the electron density is much reduced. The true Thomson optical thickness, from equation (5), is therefore less: $\tau_{\rm T} \sim n\sigma_{\rm T} ct_r \sim 0.06$. We conclude that the strong Hα and Hβ lines from the cloud should be redshifted by ~ 270 km s^{-1} at most, and should be narrow, containing only a weak scattered component broadened by ~ 400 km s^{-1} at most. This is not compatible with the observed spectra (Blanco *et al.* 1987).

We must add a word about possible self-absorption effects in visible lines. Hillebrandt *et al.* (1987) stated without proof that a cloud of this sort has large optical thickness in the Balmer lines, and implied that its emission is mainly in the continuum. We disagree. Useful data for estimating optical thickness at Hα line center, and the associated transfer effects, are given by Cox and Mathews (1969; cf. Hummer and Storey 1987). Their equation (9) shows that, for $n > 10^5$ cm^{-3}, the optical thickness $\tau_{2\alpha}$ is $\approx 2 \times 10^{-4} S_{\rm pc} n$, where $S_{\rm pc}$ is the dimension of the H II region in parsecs. In our high-density case, $S_{\rm pc}$ is not the radius of the cloud or the distance from the SN, but rather the thickness $\sim ct_r$ of the ionized region at any given time, by the same argument as above. (Behind the recombination front, where recombination and the associated cooling have occurred, the population of the 2*s* state and therefore the Hα absorption are much reduced.) Our equation (5) then shows that $\tau_{2\alpha} \approx 6$, independent of n at high n. This is not large enough to change line strengths much, and in any case the first-order effect is to reduce Hβ, Hγ, ..., and *increase* Hα emission. Absence of the Balmer lines in the observed spectrum cannot be due to this effect. It is unclear, by the way, whether Dopita *et al.* (1987) neglected $\tau_{2\alpha}$; their published computation includes no mention of an optical thickness parameter.

Finally, we note that the positive observation (Nisenson *et* al. 1987) at λ5330 with $\Delta m \approx 3.0$ and $\Delta\lambda = 100$ Å cannot be explained in a fluorescence model. There are no plausible lines in this filter.

A referee has asked us to consider the possibility of a fluorescing cloud moving at high velocity, even a weakly relativistic velocity, $\beta \sim 0.1$. The emission lines would then be shifted out of the narrow-band filters and might also be broadened greatly by differential Doppler shifts within the cloud. Our calculations of fluxes in these filters then clearly would not apply, and it may be possible to "hide" the line fluxes from the mystery spot within the SN spectrum. Viewed as a loophole for saving a fluorescence model, however, this scenario has serious drawbacks: (1) Removing the Hα line from the Hα filter makes it even more difficult to explain the high observed brightness in that filter. (2) As we argued above, there is no plausible mechanism for a normal interstellar or circumstellar cloud to acquire a velocity of even 10^3 km s^{-1}, let alone 3×10^4 km s^{-1}. Such a cloud would have to be an ejecta from the SN itself. (3) Such an ejecta, with $\beta \sim 0.1$, would have to have left the SN some months *prior to* core collapse, because the time delay, from equation (1), is $t_d \gtrsim 190$ days for $\beta \sim 0.1$.

The last consideration tends to push us toward a larger β. The high-velocity cloud model then belongs with jet models (Rees 1987; Piran and Nakamura 1987; Colgate *et al.* 1988) or condensed-ejecta models (Carlson, Glashow, and Sarid 1987; Colgate *et al.* 1988; Goldman 1987) and is really beyond the scope of our paper. Such a cloud, with $\beta \sim 0.1$ or $\beta \approx 1$, would interact with the ambient circumstellar medium at a working surface at the leading side, converting kinetic energy to thermal energy. Its energy budget and emission spectrum would be very different from those of a fluorescent cloud. These models too have problems with the observational constraints (Phinney 1987, 1988).

III. A REFLECTION MODEL

We turn now to the alternative possibility of dust reflection. In fact we have neglected dust in the discussion of fluorescence above. Both fluorescence and reflection could occur at the same cloud. If the cloud has normal interstellar dust at normal abundance, the visual optical thickness for dust extinction along a radius is (Spitzer 1978, pp. 154–164)

$$\tau_e \approx 4.6 \times 10^{-22} nAl\ . \tag{9}$$

In the fluorescence model discussed above, with $n \sim 3 \times 10^7$ cm^{-3} and $A \sim \frac{1}{2}$, this is $\tau_e \sim 300$. Thus dust absorption would be important. With so many scatterings, the fluorescent lines would be suppressed if the dust were present, even if the dust albedo were quite close to unity.

In a model relying mainly on reflection, we are no longer concerned about absorbing the UV burst. We need only a moderate τ_e ($\gtrsim 1$) to reflect the steady radiation of the SN, so we can set the gas density lower, $n \gtrsim 10^5$ cm^{-3}. At this density, the cloud could be a remnant of a red giant wind (Dopita *et al.* 1987). We obtain a generous estimate of the cloud brightness by assuming that $\theta \approx \pi/2$, that the dust albedo is unity, and that all radiation striking the cloud is reflected isotropically. The magnitude difference Δm is then just $2.5 \log_{10} (4\pi/\Omega)$, with $4\pi/\Omega \approx 4/A^2$. For $A = \frac{1}{2}$, we have $\Delta m \approx 3.0$ mag, which is bright enough to agree with the λ6563 observation. Fluorescence could make a small additional contribution. If the limit (Meikle, Matcher, and Morgan 1987) $A < 0.27$ is confirmed, however, then we have $\Delta m > 4.3$ mag, which is too faint. Because dust scattering depends only weakly on wavelength, this problem is in no way relieved by giving the cloud a velocity, large or small. In calculations for a detailed model, lacking the generous assumptions above, we might well lose another magnitude to albedo, phase function, and geometry (e.g., shadowing). In addition, the SN brightened (Blanco *et al.* 1987) by ~ 1.1 mag in m_R (and apparently also around $\lambda 6563$) from February 24 to April 1. Because of the time delay in reflection, this should further increase the expected Δm temporarily. (This effect should reverse later.) Thus we cannot be optimistic about a dust reflection model, although the numbers are close enough to be tantalizing. Further analyses of the interferometric data should include an exploration of the parameter space allowed for source models having larger angular size, possibly with various shapes, such as a lunette. If such analyses show that $A > 0.27$ is, in effect, permitted, there may be some scope for dust models, perhaps exploiting a forward-throwing phase function. The lack of any positive detection of the companion after 1987 April is, however, a serious difficulty for any dust reflection model. The visual luminosity of the SN peaked and began to drop after mid-May, which should have caused the echo to *increase* in relative brightness (decrease in Δm) for a month or so, because of the time delay. We could assume that all of the dust happened to evaporate between April 15 and May 30, but this would require excessively fine tuning of the model.

No direct observations of the mystery spot itself for polarization have been reported. Spectropolarimetric studies of the SN (Cropper *et al.* 1988; Mendez *et al.* 1988), which necessarily include any contribution made by the spot, show, after correction for foreground, a time-variable intrinsic linear polarization $\lesssim 1\%$ at a position angle quite close to that observed for the position of the spot ($\approx 194°$; Nisenson *et al.* 1987). Cropper *et al.* (1988) suggest that this agreement is significant, though their own data are not contemporaneous with positive observations of the spot. Mendez *et al.* (1988) do report observations continuing through March and April, which suggest some change in polarization around March 25 (Karovska 1988)—the date when the spot was first looked for (and seen). We refer the reader to these papers, with the following comments: (1) Interpretation of these data is complicated by the large and uncertain correction for foreground interstellar polarization in the Galaxy and the LMC; (2) the intrinsic linear polarization inferred by these observers is *orthogonal* to that expected from a scattering cloud at the position angle of the spot; and (3) the polarization data do, in principle, contain much information about the evolution of the SN envelope (Brown and McLean 1977; Shapiro and Sutherland 1982; McCall 1984*b*; Jeffery 1987).

Nova Persei 1901 provides a precedent for polarization observations, but unfortunately the observations were negative. The brightest reflecting cloud near Nova Persei, which was at $\theta \sim \pi/2$, should have shown polarization (Katz and Jackson 1988; Felten 1988), but failed to do so when observed rather tardily (Perrine 1902).

Preexisting circumstellar dust will be partly evaporated by a supernova (Dwek 1983; Pearce and Mayes 1986). For dust temperatures above ≈ 300 K, the equilibrium temperature of a dust particle of radius a at a distance $R_{\rm pc}$ pc from the SN is (Dwek 1988)

$$\begin{aligned} T_d(\mathrm{K}) &\approx 115[L_{41}/\alpha(\mu\mathrm{m})R_{\rm pc}^2]^{0.18} \quad \text{for graphite grains}\,, \\ &\approx 62[L_{41}/\alpha(\mu\mathrm{m})R_{\rm pc}^2]^{0.25} \quad \text{for silicate grains}\,, \end{aligned} \tag{10}$$

where L_{41} is the SN luminosity in units of 10^{41} ergs s^{-1}. A grain vaporizes if it is maintained at this temperature for a time (e.g., Draine and Salpeter 1979)

$$t_v(\mathrm{s}) \approx 7.6 \times 10^{-9}\alpha(\mu\mathrm{m}) \exp{(U_0/kT_d)}\,, \tag{11}$$

where U_0 is 7.35 or 5.7 eV for graphite or silicate grains, respectively. The evaporation is sensitive to T_d because of the exponential in equation (11). It is easy to show from equations (10) and (11) that evaporation occurs mainly during the UV burst, because L_{41} is highest then. For a Type II SN, Pearce and Mayes (1986) in their study of evaporation assumed an optical luminosity too high for SN 1987A. Fortuitously their results can be applied, very roughly, to evaporation by the TWOBF10 UV burst, because they had $L_{41} \approx 300$. They find that, at distance $R \approx 0.016$ pc, silicate grains will evaporate, but graphite grains with $a > 0.03$ μm will remain refractory. These results overestimate the evaporation, because the duration of the UV burst is short. Our own rough estimate, from equations (10) and (11) and the light curve of the TWOBF10 burst, suggests that large silicate grains and essentially all graphite grains will survive. These calculations are sensitive to properties of the burst and to grain emissivities, but they suggest that small dust grains may be depleted at distance l from the SN. If the dust layer in the cloud is thick ($\tau_e > 1$) before the explosion and remains thick afterward, small grains may be depleted in the surface layer only.

This is interesting because of the observed color of the companion, which is detected at $\lambda 5330$ but is marginal or invisible at shorter wavelengths. In a reflection model, this implies that the cloud is red. Most reflection nebulae are blue, but recent work (Witt *et al.* 1987) suggests that red ones arise from the absence of small grains. Red color therefore does not rule out a reflection model. If a light echo (Schaefer 1987) is ever detected from SN 1987A, the color may contain information about the size distribution of dust surviving in the cloud, and hence about the UV burst.

The subsequent optical radiation from the SN at (Woosley, Pinto, and Ensman 1988) $L_{41} \approx 10^{0.4}$ will maintain surviving dust, at distance l, at a temperature $T_d \approx 960$ K (eq. [10], for 0.1 μm graphite grains). If the cloud is optically thick and as large as $A = \frac{1}{2}$, and if it reradiates thermally roughly half of the energy falling on it, a thermal spectrum will be seen with peak $F_\nu \approx 18$ Jy at $\lambda_{\max} \approx 5.4$ μm. Infrared observations (Gregory and Elias 1987; Aitken, Smith, and Roche 1987; Witteborn *et al.* 1987) allow the presence of such a component, and in fact the observed spectrum displays a shoulder at $\lambda > 6$ μm which might be a manifestation of it. We reiterate that, although these observations allow the presence of a dust cloud, the problem of accounting for the high optical brightness of the companion object in a reflection model is a difficult one if all the speckle observations are correct.

In closing we should mention that the large-scale light echoes recently detected around the SN show a strong brightness gradient from one side of the SN to the other, in the sense that they are less bright on the side where the mystery spot was seen earlier. (Note, however, that these arcs are seen at distances of 0".5 to 1' from the SN, whereas the mystery spot was only 0".06 away.) Suntzeff *et al.* (1988) have suggested that this gradient is somehow related to the mystery spot. The implication seems to be that the mystery spot might itself have been a reflection echo, and might have cast a shadow which now affects the large arc-shaped echoes. Even apart from the difficulties of making a reflection model of the mystery spot, we feel that there are geometrical problems with this suggestion. We defer further discussion to a subsequent paper (Felten and Dwek 1989).

Consideration of the physical points raised here will suggest further observations. Of course it is important that more adventurous theories of the companion object (Rees 1987; Piran and Nakamura 1987; Carlson, Glashow, and Sarid 1987; Colgate *et al.* 1988; Goldman 1987) be similarly tested against existing data.

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Note added in proof.—In a revised version of the manuscript by Chalabaev, Perrier, and Mariotti (1988*b*), their derived upper limit on the strength of the UV burst no longer disagrees with model 10H of Woosley (1988).

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