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STAR-FORMING REGIONS NEAR THE SUPERNOVA REMNANT IC 443

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ABSTRACT

The supernova remnant (SNR) IC 443 (3C 157), along with W28, W44, S147, and HB 21, represents a growing number of examples where SNRs appear to have collided with nearby molecular clouds or are surrounded by dense shells of neutral hydrogen. In the case of W28, far-infrared observations have shown that a massive, O-type star and possibly a pre–main-sequence B-type star are associated with the molecular cloud and its environment. In the current study, the northern component of the IC 443 molecular cloud has been detected at 20, 27, and 93 μm by the Far Infrared Sky Survey Experiment. The bolometric luminosity of this far-infrared source is $\sim 130\ L_{\odot}$, consistent with the expected luminosity of a B7 V star. From the far-infrared and radio observations we describe the energetics of this region, comparing it with other known examples of SNR/molecular cloud associations. We also discuss these findings in the context of theoretical models where SNRs trigger star-forming activity in nearby molecular clouds.

Subject headings: nebulae: individual — nebulae: supernova remnants — stars: formation

I. INTRODUCTION

The supernova remnant (SNR) IC 443 has been the subject of a great many investigations over the years (see Duin and van der Laan (1975); Cornett, Chin, and Knapp (1977), hereafter CCK, for reviews), and a glance at the Palomar Sky Survey red print (Fig. 1 [Pl. 5]) shows us part of the reason for this interest. IC 443 is a large, well-formed, spherical shell with a diameter of nearly 1°, bearing a striking resemblance to the filamentary structure of the Cygnus Loop (van den Bergh, Marscher, and Terzian 1973, hereafter BMT).

IC 443 is apparently quite young. An age based on the spin-down rate of the associated pulsar PSR 0611+22 suggests 65,000 yr (Davies, Lyre, and Seiradakic 1972); Lozinskaya (1969, 1975) has estimated an age of 50,000 yr based on the expansion velocities of the filaments, while a study of the X-ray emission by Parkes *et al.* (1977) yields an age as low as 12,000 yr.

According to CCK, the molecular cloud appearing in CO consists of two emission peaks. The main peak is located diagonally across the face of the SNR and corresponds to a broad gap in the optical filaments of the SNR. This gap is probably due to obscuration by the molecular cloud itself. The H_2 column density according to CCK is 2×10^{21} cm^{-2}, assuming $[CO/H_2] \sim 2 \times 10^{-5}$. A cloud thickness of 3 pc implies a molecular hydrogen density of about 220 cm^{-3} and a total mass of $\lesssim 10^4\ M_{\odot}$. Giovanelli and Haynes (1979) as well as CCK conjecture that the SNR may have detonated near the periphery of a preexisting molecular cloud with a preshock density of a few times 10^2 cm^{-3}, and that a vestige of the original cloud is still present in the form of the CO/H I cloud seen to the northeast of the SNR. This is also consistent with H I observations by Locke, Galt, and Costain (1964) and Akabane (1966), and more recently by DeNoyer (1977, 1978) and Giovanelli and Haynes (1979), which show that most of the observable H I beyond the optical shell appears at negative velocity; very little H I emission is seen at positive velocity corresponding to the back side of the shell.

The CO emission, along with the H I, borders the filamentary optical emission to the northeast of the SNR and is also consistent with the optical (Lozinskaya 1969, 1975; Parker 1964), radio continuum (Duin and van der Laan 1975), and X-ray evidence (Winkler and Clark 1974; Charles, Culhane, and Rapley 1975; Malina, Lampton, and Bowyer 1976), suggesting that the SNR has encountered a dense molecular cloud in this region.

To the northeast of the SNR, a secondary concentration of CO emission is located at the position R.A. (1950) = $6^{h}15^{m}.5$, Decl. (1950) = 23°21′. It is adjacent to a reflection nebula associated with the B9 II star SAO 078225 about 1° beyond the optical edge of the SNR. This secondary emission peak was observed by CCK at several angular scales, and the cloud appears to be inhomogeneous, containing a clumpy component at scales of less than 1 pc.

II. DISTANCE

Although IC 443 and its surroundings have been frequently studied, there exists as yet only a loose consensus as to the distance of the SNR and the molecular cloud. Estimates for the SNR ranging from 0.5 kpc (Malina, Lampton, and Bowyer 1976), 1.5 kpc (Sharpless 1965), and 3.0 kpc (Duin and van der Laan 1975) have been offered, depending on whether the UV, optical, or radio-emission features were considered. Adjacent to IC 443 is the Gem OB1 association that appears to be the source of the illumination of the nearby H II region S249. Hardie, Seyfert, and Gulledge (1960, hereafter HSG) have shown that the 11 OB supergiants in Gem OB1 show less of a spread in distance, with an average value of 1.6 kpc, and may constitute a physical association. The approximate spatial coincidence between Gem OB1 and IC 443 is usually taken to imply that 1.5 kpc is a better estimate for the distance to IC 443. Recent optical studies of the nearby H II region S249 by Fesen (1984) also suggest that much of the filamentary structure near IC 443 is also at a distance of 1.5–2 kpc. The most consistent estimate, based on the SNR surface brightness, the pulsar spin-down rate, and the young Gem OB1 supergiants, is 1.5 kpc. To facilitate a discussion of the energetics of this

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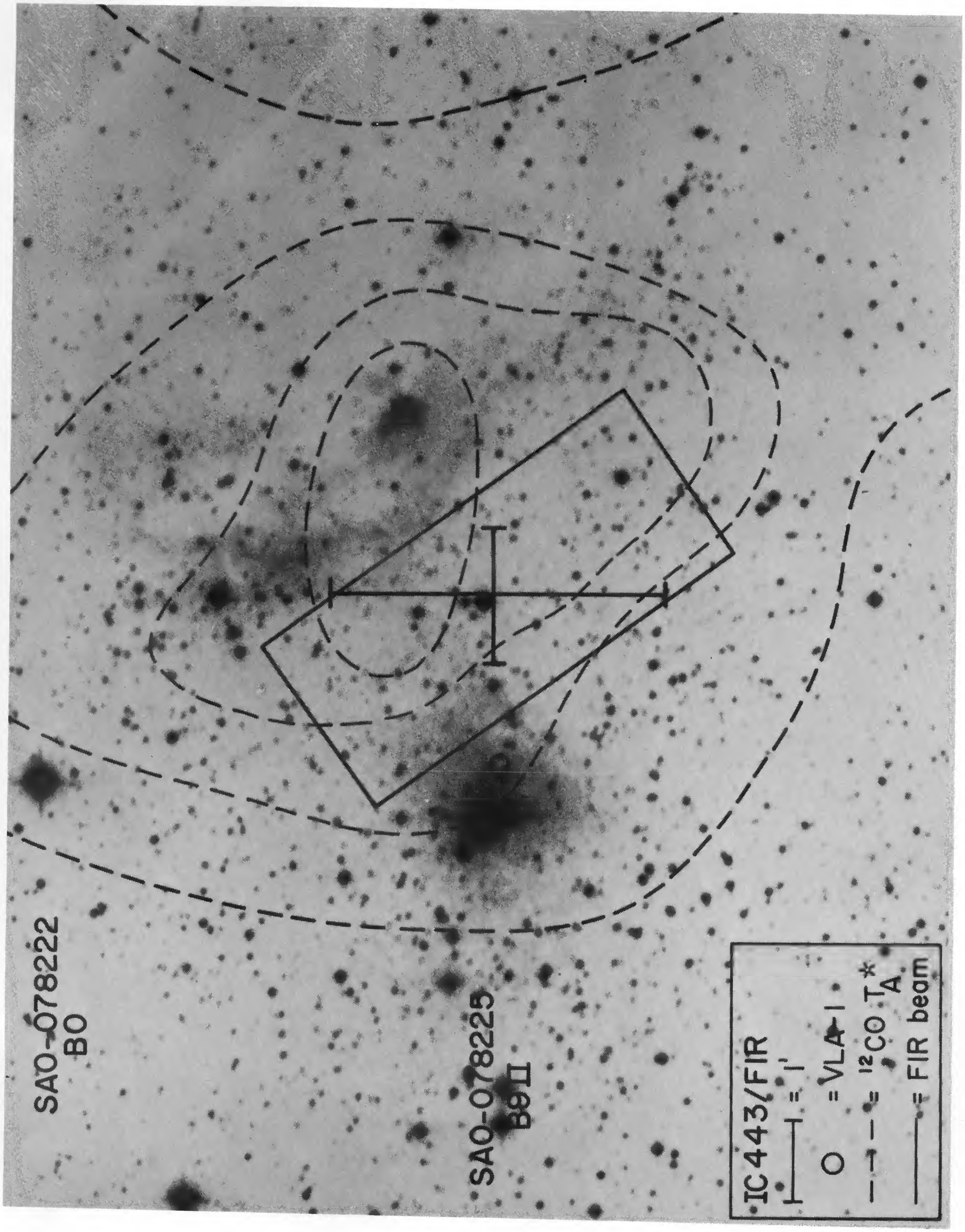

FIG. 1.—The location of FIRSSE 158, VLA 1, and the molecular cloud, superposed on a PSS red print of the region

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region, we will hereafter adopt 1.5 kpc as the most likely distance to this complex.

III. FAR-INFRARED OBSERVATIONS

The instrumentation and calibration of the Far Infrared Sky Survey Experiment (FIRSSE) has been described in detail by Price, Murdock, and Shivanandan (1983) and by Price *et al.* (1983). Briefly, the beam size at 20 and 27 μm was $2'.5 \times 10'$, while at 93 μm a larger beam of $5'.3 \times 12'$ was used. From the calibration procedure, the rms photometric uncertainties at 20, 27, and 93 μm are correspondingly 20%, 30%, and 40%. The FIRSSE survey was able to detect a single extended source, FIRSSE 158, at $6^h15^m42^s \pm 8^s$ and $+23°20'.7 \pm 4'$. The location of this source relative to the other features in this region is shown in Figure 1. The far-infrared measurements yield fluxes of 87, 134, and 488 Jy at 20, 27, and 93 μm. FIRSSE 158 appears to be offset from the ^{12}CO emission peak of the molecular cloud and is not coincident with either the optical emission nebula surrounding SAO 078225 or the filamentary reflection nebula to the northwest of the CO peak.

a) *Spectrum and Luminosity*

A series of dust models was fitted to the far-IR spectrum for FIRSSE 158 by computing the FIR emission from a single, spherically symmetric, homogeneous, optically thin, and isothermal source that just fills the 93 μm beam. As Figure 2 illustrates, a dust temperature of 65 ± 5 K provides the best overall fit to the data in all three bands. A λ^{-1} emissivity dust grain also yields a better fit than does a simple, 65 K blackbody when normalized to the same flux scale, the latter predicting a lower 20 μm flux than can be reconciled with the photometric uncertainties in this band.

The total luminosity of FIRSSE 158 can be determined by directly integrating the spectrum fitted to the measurements. The bolometric correction, assuming a 65 K, λ^{-1} source spectrum, is 2.4, so that the bolometric luminosity corresponds, at a distance of 1.5 kpc, to about $130 \pm 50\ L_{\odot}$ within the 93 μm beam.

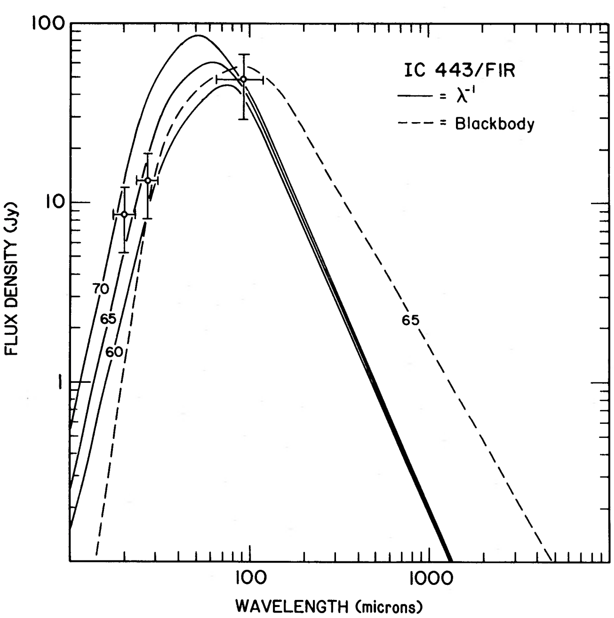

FIG. 2.—Far-infrared spectrum of FIRSSE 158 showing the FIRSSE observations at 20, 27, and 93 μm together with the best-fit source models for the underlying dust spectrum based on a model containing a uniform, isothermal, and spherically symmetric dust distribution.

b) *Dust Temperature and Optical Depth*

The FIR color temperatures based on the 27 and 93 μm data yields $T_c = 70 \pm 10$ K. The brightness temperature, corresponding to the 93 μm flux measured by a beam size of $5'.3 \times 12'$, yields T_B (93 μm) $= 13.5 \pm 0.5$ K. Taken together, T_B and T_c imply an unusually low optical depth of τ (93 μm) $= 0.00002$. This estimate is, of course, very sensitive to the angular size assumed for FIRSSE 158, which, in turn, determines the value for T_B.

The 93 μm optical depth inferred from the ^{12}CO column density of 4×10^{16} cm^{-2} derived by CCK, together with the FIR optical depth relation of Evans, Blair, and Beckwith (1977) of

$$\tau(\lambda) = 10^{-18}(\lambda/100\ \mu\mathrm{m})^{-1}N(^{13}\mathrm{CO})\ , \quad (1)$$

suggests $\tau(93\ \mu\mathrm{m}) = 0.001$ at the CO peak assuming $N(^{12}\mathrm{CO})/N(^{13}\mathrm{CO}) = 40$. The discrepancy between the two methods of determining $\tau(93\ \mu\mathrm{m})$ can be resolved if the angular size for FIRSSE 158 is $\sim 1'$, in which case $T_B \approx 18$ K for $\tau(93\mu) \approx 0.001$. Assuming that T_B is 16 ± 2 K and $\tau(93\ \mu\mathrm{m}) \approx 0.001$, the estimated dust temperature will be 54 ± 20 K, with the best-fit dust model suggesting that $T_d \approx 65 \pm 5$ K, as shown in Figure 1.

The maximum ^{13}CO emission from the northeast section of the molecular cloud, as measured by CCK, is $T_A{}^* = 0.8$ K at an optical depth of 0.28. The inferred gas temperature is 6 K, which is an upper limit to the gas temperature at the location of the FIR peak, since the ^{13}CO and FIR peaks are not coincident. Clearly, the gas temperature is significantly below that of the dust grains at the same location in the cloud. This situation can be understood in terms of the inefficient coupling between the gas and dust components at the low, 200 cm^{-3}, densities inferred for the molecular cloud. Under these circumstances, the cooling of the gas component through radiation is more efficient than the heating of the gas by collisions with the much warmer dust, so that $T_g \ll T_d$.

IV. RADIO CONTINUUM OBSERVATIONS

A region $30' \times 30'$ centered on the secondary CO peak and extending south to the periphery of the SNR was mapped at 2, 6, and 20 cm with the Very Large Array (VLA) of the NRAO[2] between 1984 January 11 and 12 to determine whether compact radio sources associated with young, embedded OB stars may exist in this region. A single, unresolved source 0616+2329 was detected in the immediate vicinity of SAO 078225. At a position R.A. (1950.0) $= 6^h16^m14^s.076$, Decl. (1950.0) $= 23°17'31''.45$, SAO 078225 is surrounded by an optical emission nebula with VLA 1 embedded in the nebulosity, 85″ to the west of the star in the direction of the FIR/CO peak.

The 6 and 20 cm fluxes for 0616+2329 of 14 and 22 mJy imply a spectral index of -0.37, which is quite steep for a thermal source and is more in character with known extragalactic, "flat-spectrum" radio sources. The integral radio-source distribution function described by Bennett *et al.* (1983), suggests that the estimated number of spurious extragalactic radio sources between 12 and 16 mJy in our survey should be

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of order unity. In view of the spectral index, the inferred spectroscopic class, and the number of expected spurious sources in a survey of this size, the conclusion that the 0516+2329 source is indeed extragalactic seems inescapable.

V. THE NATURE OF THE DUST HEATING IN FIRSSE 158

a) External Heating

There are two possibilities available for explaining the luminosity and temperature of FIRSSE 158: the heating sources may be either internal to the molcular cloud or external. To evaluate the latter possibility, the potential external heat sources need to be identified. In the area of the sky within 1° of FIRSSE 158 there are 11 OB stars whose spectroscopic distances can be estimated and whose distances are in the range 1–2 kpc. Table 1 includes a compilation of the spectral classes (col. [3]), apparent magnitudes (col. [6]), and absolute magnitude (col. [7]) for each of the candidates, based on the spectroscopic study of the Gem OB 1 association by HSG. The line-of-sight absorption (col. [8]) may be estimated by using $A_v = 3.0 \times E(B-V)$, and from this the spectroscopic distance in parsecs (col. [9]) follows. The stellar luminosities in log solar units (col. [10]), surface temperatures (col. [4]), and radii in solar units (col. [5]) were obtained from the compilation of OB-star properties by Panagia (1973). The average distance to these candidates is 1400 ± 250 pc. Since the assumed distance to IC 443 and the molecular cloud is 1.5 kpc, a distance of 1.5 kpc for the stars will be used in the following analysis. To estimate the stellar luminosity at the location of FIRSSE 158 contributed by each star, the angular separations between the stars and the FIR source are converted to an equivalent linear distance in parsecs, assuming a distance of 1.5 kpc (col. [11]). The stellar luminosity in solar units available to the far-infrared source is then computed (col. [12]) by reducing the stellar luminosity by the solid angle subtended by the FIR source. The estimated luminosities are, of course, only upper limits, since we have used the projected distances between the stars and FIRSSE 158, which will be smaller than the actual physical separations. Clearly, the total available luminosity, 20,000 $L_\odot$, is more than adequate to supply the 130 $L_\odot$ detected at the location of FIRSSE 158. In particular, the nearby B0 III star SAO 078222 appears to account for over half the luminosity falling on the FIR source.

A major drawback to this scenario involves the high temperature inferred for FIRSSE 158 of 65 K. In Table 1, the anticipated temperatures to which the dust grains may be heated (col. [11]) has been estimated for each star by using

$$T_d = T_*(r_*/R)^{2(4+N)}\ , \tag{2}$$

where $n = 1$ has been chosen in accordance with the best spectral fit in Figure 2. T_* and r_* are the photospheric temperature and radius of the star, and R is the distance between the star and the FIR source. Although there appears to be at least 20,000 $L_\odot$ available in the ambient stellar radiation field falling on the molecular cloud, none of the candidate stars seem to be capable of producing, simultaneously, the luminosity and temperatures associated with the FIR source.

The possibility that FIRSSE 158 is externally heated by nearby OB stars would appear to be excluded by the high temperatures inferred for the FIR source based on the 20 and 27 μm observations.

b) Embedded Stars

The implied existence of possibly two dust components contributing to the emission of FIRSSE 158 agrees with most models of what dust-embedded stars ought to look like in terms of their FIR properties. The 65 K component should be found nearer to the photosphere of the embedded star than the cooler, 30 K component.

Based on our failure to detect any radio continuum emission at 6 cm from FIR 158 above 1 mJy using the VLA, we can set an upper limit to the spectral type of the embedded star. The relationship between the Lyman flux N_L, the 6 cm radio flux density S, and the distance D, as given by Mezger, Smith, and Churchwell (1974), implies $N_L = 8.9 \times 10^{44} S\ (\mathrm{Jy})\ D^2\ (\mathrm{kpc})\ \mathrm{s}^{-1}$. For $S = 1$ mJy and $D = 1.5$ kpc, $N_L = 2 \times 10^{42}\ \mathrm{s}^{-1}$, which implies that the embedded star must have a spectral class later than B2 V. The FIR luminosity, assuming all the stellar continuum is absorbed by dust grains, implies that the source contains no more than one, B7 V (Morton and Adams 1968). If FIRSSE 158 contains a single B7 V star, one can estimate a size for the region where the optical depth is unity by using equation 2, together with a photospheric temperature of 13,600 K, $T_d = 65$ K, and a radius less than 3′ (1.5 pc). The inferred photospheric radius would then be less than 100 $R_\odot$. Dust grains are expected to evaporate at temperatures of ~2000 K, so that the circumstellar dust shell has an inner radius, of about 80 AU. Provided that the embedded heating source is a single star, FIRSSE 158 appears to be a cocoon-like star. This explanation can be made to fit the far-infrared and radio observations more easily than the hypothesis of an externally heated far-infrared source.

TABLE 1

CANDIDATE STARS FOR EXTERNAL HEATING OF FIRSSE 158

HD (1)	SAO (2)	Spectral Type (3)	T^* (4)	r^* (5)	m_v (6)	M_v (7)	A_v (8)	d (9)	L^* (10)	r (11)	L_d (12)	T_d (13)
254042......	078151	B0.5 IV	25500	9	8.95	−4.2	1.95	1740	4.4	20.6	103	16
43384......	078176	B3 Iab	16100	51	6.26	−6.5	1.92	1450	5.2	11.5	220	25
254577......	078193	B0.5 II	24000	18	9.08	−5.0	3.27	1450	5.0	24.6	300	18
254699......	078198	B1 V	22600	6	9.02	−3.1	2.00	1050	3.95	6.7	360	19
254755......	078203	O9 V	34500	8	8.86	−4.6	2.61	1450	4.9	17.3	485	22
43703......	078205	B1 IV	22000	8	8.65	−3.8	2.20	1150	3.8	8.6	160	18
43753......	078211	B0.5 III	25000	10	7.93	−4.7	1.77	1500	4.6	8.8	880	23
43818......	078222	B0 III	29300	13	6.92	−5.4	1.83	1250	5.0	4.0	12300	41
255091......	...	B2 V	20500	6	9.54	−2.0	1.40	1050	3.7	13.6	50	13
255134......	...	B1 V	22600	6	9.17	−3.8	1.89	1650	3.9	2.7	2200	27
255168......	...	B1 V	22600	6	9.68	−3.1	1.53	1700	3.9	14.0	83	14

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c) *Did IC 443 Trigger the Formation of FIRSSE 158?*

It was originally suggested by Opik (1953) and more recently by Sancisi (1974) and Assousa and Herbst (1976) that the detonation of a massive star produces an expanding SNR that may then impact a dense molecular cloud, triggering star formation. As examples, CMa R1, Orion A, Cep OB3, Sco OB1, Per OB1, and Cep OB4 have been cited as cases where this mechanism has operated in the distant past (about 10^6 yr B.P.). The SNRs S147 (Wooten, Blair, and Vanden Bout 1975), W44 (Wooten 1976), W28 (Wootten 1981; Odenwald *et al.* 1984), and G109.1 − 1.0 (Gregory *et al.* 1983), as well as IC 443 (Cornett *et al.* 1977), have also been implicated in triggering star-forming activity in nearby molecular clouds in the more recent past (10,000 to 60,000 yr B.P.).

In spite of the growing number of examples, only W28 and IC 443 have been studied in the FIR to determine whether star-forming activity has occurred in the youngest of these potential SNR-triggered candidates. Both the far-infrared surveys were capable of detecting the luminosity from the most luminous OB stars to have formed in the last 10^5 yr in each association. In the case of IC 443, the currently active site for the formation of massive stars is the secondary CO peak located at least 12 pc from the optical rim of the SNR. Under these circumstances it seems unlikely that the SNR could have had a substantive effect on a region this distant. The FIRSSE 158 source, as a dust-embedded stellar object, cannot be more than a few times 10^5 yr old plus an unknown time period corresponding to its current main-sequence age. The SNR, on the other hand, is not likely to be more than a few times 10^4 yr old. The conclusion that the star-forming events leading to FIRSSE 158 substantially *predate* the supernova detonation seems inescapable.

For the high-mass stars, what we seem to be witnessing, at least in the case of IC 443, is the formation of a late B-type star at the northern end of the molecular cloud followed $\sim 10^5$ yr later by the detonation of a more massive star 12 pc or more distant, in the southern part of the cloud. This not only demonstrates that supernovae are not always essential to the star formation process, but also shows that conditions leading to massive star formation do not necessarily occur at the same time within a single molecular cloud.

We would like to acknowledge the helpful comments and discussions with Dr. Phil Schwartz on interpreting the CO data and the guidance of Dr. Ken Johnston in helping one of us (S. F. O.) reduce the VLA data. We would also like to thank the VLA staff for their patience in guiding a new user through the intricacies of VLA observing and data calibration.

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