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IRAS[1] SOURCES ASSOCIATED WITH SHOCKED GAS REGIONS IN IC 443

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ABSTRACT

Although many supernova remnants are expected to interact with surrounding clouds, only IC 443 exhibits convincing evidence of such interactions, characterized by highly perturbed gas with very large ($\geq$ 20 km s^{-1}) velocity dispersions. Large-scale, high-resolution CO observations with the 14 m telescope of the Five College Radio Astronomy Observatory have revealed seven such regions, five newly discovered, in IC 443. A comparison with the *IRAS Point Source Catalog* shows that three bright, unidentified far-infrared pointlike sources display good positional coincidence with clumps of highly perturbed gas. Chance superposition of the clumps and the *IRAS* sources is shown to be highly unlikely. We suggest that the *IRAS* sources may delineate a new class of infrared objects associated with supernova remnants.

Subject headings: infrared: sources — nebulae: supernova remnants — stars: formation

Roughly one-half of all galactic supernova remnants (SNRs) are located near large molecular clouds (Huang 1985), presumably the parent clouds of the stellar progenitors. A significant fraction of these remnants may be expected to interact with surrounding clouds when the supernova (SN) shocks expand into the interstellar medium. Nonetheless, after several attempts (e.g., Cornett 1977; Scoville *et al.* 1977; Wootten 1978) to search for such interactions, IC 443 remains the only SNR exhibiting convincing evidence for cloud-remnant interactions, characterized by broad-velocity emission ($\geq$ 20 km s^{-1}) and the enhanced abundance of certain molecular species at three positions (see DeNoyer and Frerking 1981 and references therein). Although the exact nature of these regions remains unclear, the very wide spectral lines are usually interpreted as highly agitated, postshock gas. In this *Letter*, we will use the term "shocked regions" to refer to these highly perturbed areas.

Since the lack of systematic surveys may account for the apparent paucity of shocked regions in SNRs, we observed a $50' \times 50'$ region spaced by $2'$ on the face of IC 443 in the CO($J = 1 \rightarrow 0$) line in order to study further the distribution and characteristics of the shocked gas. Additional observations at $1'$ spacing were carried out in the immediate vicinity of all map positions where broad CO emission lines were detected. The observations were made with the 14 m telescope of the Five College Radio Astronomy Observatory; the combination of high angular resolution ($45''$ at 2.6 mm) and high sensitivity (single-sideband receiver temperature $\leq$ 200 K) make this a suitable instrument for such a study. Details of the observations will be published elsewhere.

Figure 1 shows schematically the outlines and locations of seven shocked CO clumps detected in our program, five of which were previously unknown. Each has been designated alphabetically, maintaining conformity with DeNoyer's (1979) original nomenclature. The sizes of the clumps shown in Figure 1 reflect both the sensitivity limit of our survey as well as the requirement that detectable CO emission extending over at least 20 km s^{-1} at zero power be present. Positions mapped adjacent to the clumps occasionally showed perturbed gas which did not meet the above velocity criterion, and presumably there are other locations in the SNR where perturbed gas too weak to be detected in our survey may in fact be present (see below).

Composite, spatially averaged CO line profiles are illustrated in Figure 2 for clumps B–G. Although clumps C and D appear to merge together in Figure 1, they exhibit very different line profiles and have therefore been treated as separate objects. The clumps range in size from 0.5 to 5 pc if we assume them to lie at a distance of 1.5 kpc, the distance to IC 443 (e.g., Odenwald and Shivanandan 1985). Two of DeNoyer's three shocked positions, B and C, turn out to be part of extended, shocked CO clumps. The other, designated by DeNoyer as position A, did not show a perceptible CO signature in our map. It is clear, however, that position A marks a shocked region because it exhibits broad line emission in HCO^+ and H I (Dickinson *et al.* 1980; Braun and Strom 1985). A low-noise spectrum subsequently obtained toward position A confirmed this, revealing a line profile virtually identical to that published by DeNoyer, but too weak to be detected at the signal-to-noise ratio of our survey.

By comparing our CO data toward IC 443 with the *IRAS Point Source Catalog*, we attempted to find infrared signatures of the shocked regions and to clarify their nature. Three bright ($\geq$ 40 Jy) 100 μm *IRAS* point sources lying within the face of IC 443 show good positional coincidence with regions of shocked CO (Fig. 1). One of these is near DeNoyer's position

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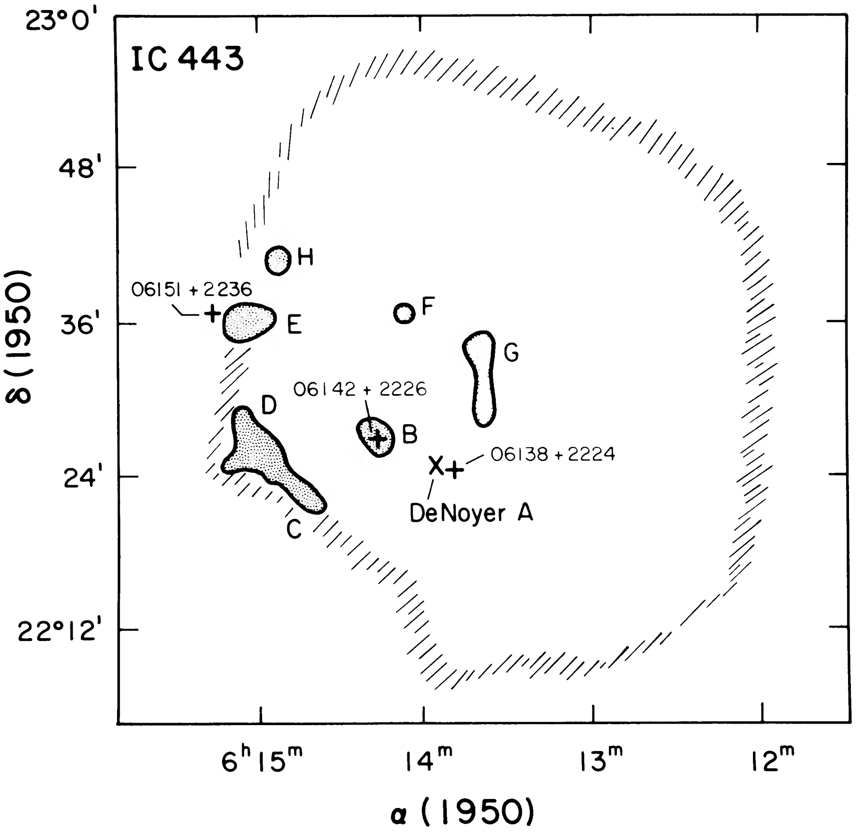

FIG. 1.—Schematic representation of the location of shocked clumps toward the SNR IC 443, as revealed by CO spectra obtained with the FCRAO 14 m telescope. DeNoyer's (1979) alphabetical designation of such regions has been extended to encompass the newly discovered clumps labeled D–H. The stippled region surrounding each clump corresponds to the area over which highly perturbed CO could be identified in our spectra. Also shown are the three brightest *IRAS* point sources identified in Table 1 and the outline of the optical SNR.

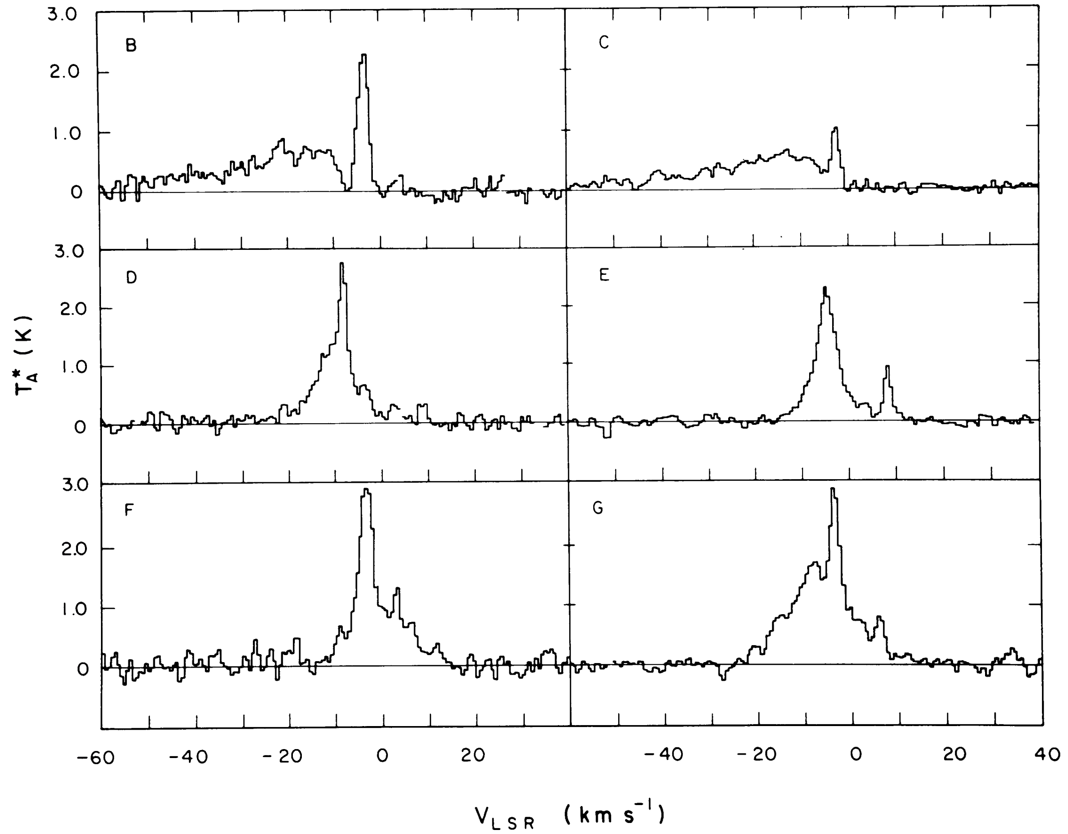

FIG. 2.—CO profiles averaged over the stippled areas indicated in Fig. 1. Only clumps B and C were known previously as perturbed regions.

TABLE 1

IRAS SOURCES AT 100 MICRONS IN OR NEAR THE SNR IC 443

	FLUX (Jy)[a]					
SOURCE NAME	12 μm	25 μm	60 μm	100 μm	$T_c(K)$[b]	$L(L_\odot)$[c]
06121+2226 ...	< 0.25	< 0.33	< 0.71	6.14	...	...
06123+2254 ...	2.11	2.23	16.78:	44.65	32	114
06133+2246 ...	< 0.25	< 0.44	< 2.21	11.18	...	...
06138+2224 ...	< 0.25	< 0.41	9.07	40.70:	27	102
06142+2226 ...	0.76	< 0.62	19.72:	40.62	35	110
06147+2243 ...	< 0.32	< 0.35	4.14:	18.53	27	46
06151+2246 ...	0.49:	0.57:	10.11:	23.84	34	62
06152+2236 ...	< 0.25	< 0.29	8.43	41.10:	26	104

[a] Fluxes given in the *IRAS Point Source Catalog*. The colon denotes data of moderate quality; fluxes not marked are of high quality.

[b] Color temperature derived from the color-corrected flux ratio between 60 and 100 μm.

[c] Total infrared luminosity (from 1 to 500 μm) estimated from fluxes at 60 and 100 μm, assuming a dust emissivity index of 1 and a distance of 1.5 kpc.

A, one coincides with the center of clump B, and the third lies at the edge of clump E. While we did not point directly at the positions of the *IRAS* sources, all three were covered by our 1′ spacing follow-up maps of the clumps. However, since the size of clump A has not been measured owing to the weakness of its emission, we cannot determine whether *IRAS* 06138+2224 is actually coincident with perturbed gas. In the case of 06151+2236, follow-up observations which include the source in the antenna beam reveal perturbed gas although characterized by emission narrower than that seen toward the center of clump E and less wide than the 20 km s^{-1} criterion adopted to outline the clumps.

The *IRAS* sources are unidentified, show strong emission at 60 and 100 μm, and display weak, mostly undetected, emission at 12 and 25 μm (see Table 1). Their color temperature and total infrared luminosity fall in a narrow range: from 26 to 35 K and from 102 to 114 $L_\odot$, respectively. One more bright, unidentified 100 μm source (06123 + 2254) near IC 443 is located just beyond the boundary of the SNR and our CO map. This source has a somewhat different infrared spectrum from the previous three sources, in that it is detected at all four *IRAS* bands.

The three *IRAS* sources which lie within the boundaries of IC 443 have no counterpart in other astronomical catalogs referenced by the *IRAS Point Source Catalog*. Like many 60 and 100 μm–only sources in the *IRAS Point Source Catalog*, the three sources could be faint, uncataloged field galaxies. However, no galaxy appears at the locations of these sources on the Palomar Observatory Sky Survey prints. Alternatively, the sources could be part of the *IRAS* cirrus, but this appears to be improbable; although a clear-cut prescription is not given to determine if they are cirrus, according to the *IRAS Catalog* only a small fraction of the flux of the three point sources is likely to be due to cirrus (Beichman *et al.* 1984).

Even though the observed positional coincidences between the shocked CO clumps and the *IRAS* sources are striking, the possibility that these are due to chance cannot be ruled out. To address this issue, we searched for bright *IRAS* sources within a 10° × 2° rectangular strip centered on IC 443. This area is about 60 times larger than the SNR itself, and the choice of orientation parallel to the galactic plane helps ensure that the surface density of *IRAS* point sources is similar to that at the latitude of IC 443. Only five 100 μm sources stronger than 40 Jy were found in this region. One of the five (*IRAS* 06155 + 2319A) is coincident with the H II region BFS 51 (Blitz, Fich, and Stark 1982). The rest are those already mentioned as lying in or near IC 443. The probability that at least three positional coincidences between shocked clumps and unidentified *IRAS* point sources are purely random can be estimated by a binomial distribution to be less than 10^{-8}, because the total area occupied by the shocked clumps is roughly 10^{-3} of the 20 deg^2 area surveyed.

The main uncertainty in this estimate comes from the flux threshold (40 Jy) imposed in the selection process. To address this issue, in Figure 3 we plot the number of 100 μm *IRAS* sources detected within the 20 deg^2 strip versus flux. Sixty-two sources weaker than 10 Jy at 100 μm are found, 15 have fluxes between 10 and 40 Jy, and five are brighter than 40 Jy. Of the 62 sources below 10 Jy, only one is located in IC 443, as might be expected from a purely random distribution of sources within the 20 deg^2 strip. Roughly half of these faint sources are detected at 100 μm only and are therefore probably cirrus (Beichman *et al.* 1984). The rest may be cirrus, heated dust clumps in molecular clouds, or typical stars.

Within the boundaries of IC 443, there are three more *IRAS* sources (06133+2246, 06147+2243, and 06151+2246) with 100 μm fluxes between 10 and 40 Jy. *IRAS* 06133+2246 is probably a cirrus object because it is a 100 μm–only source. The other two have infrared spectral shapes similar to those of the three brighter sources associated with shocked regions, but have considerably weaker fluxes (Table 1). Our CO data do not reveal shocked gas toward the three weaker sources, although the possibility that such clumps are not strong enough to be detected by our survey cannot be ruled out. However, even if we lower our flux threshold to 10 Jy, the probability of a random coincidence between the *IRAS* sources and the

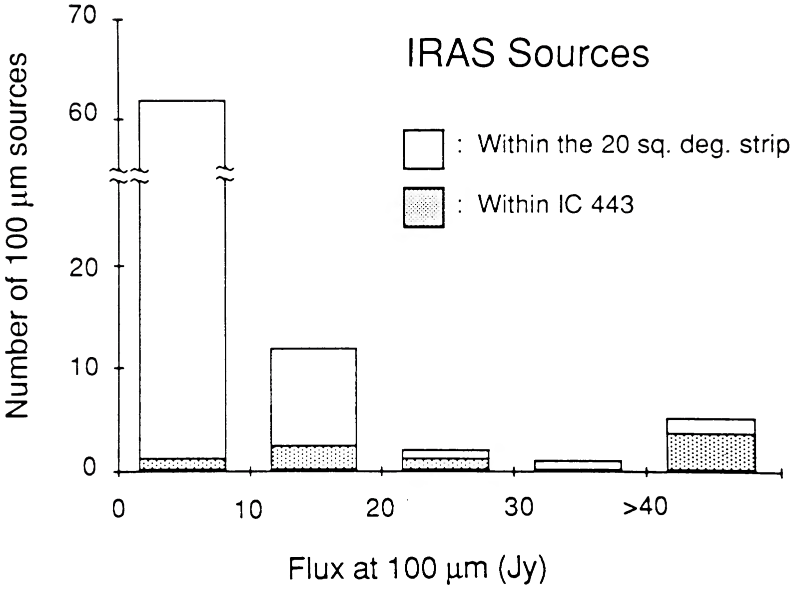

FIG. 3.—Histogram of the number of 100 μm *IRAS* sources vs. 100 μm flux. The sources both within the optical boundary of IC 443 and within a 2° × 10° strip centered on IC 443 are plotted.

shocked regions can be no more than 10^{-5}. This argues strongly for a causal relation between the *IRAS* sources and the shocked regions.

The bright *IRAS* sources in IC 443 may simply mark intensity peaks in extended, dusty regions compressed by the SN shocks. If true, it will be difficult to explain why we did not see *IRAS* sources at the *other* shocked CO clumps in IC 443. An alternative hypothesis, which deserves further observational and theoretical scrutiny, is that the *IRAS* sources may represent signatures of stellar objects, possibly cool protostars, whose formation was induced by the SN compression wave (see, e.g., Öpik 1953; Assousa and Herbst 1980). It is interesting to note that the shape of the infrared spectra of the *IRAS* sources in IC 443 closely resembles those of the young stellar objects in the dark clouds B335 and L723 (e.g., Keene *et al.* 1983). But the luminosities of the B335 and L723 sources are at least one order of magnitude smaller than those in IC 443.

In conclusion, the three *IRAS* sources associated with shocked clumps in IC 443 may delineate a new class of infrared object. The presence of these sources should offer a potentially productive means to search for highly perturbed gas in SNRs, and a systematic search for shocked clumps may provide a unique opportunity for studying both the outcome of shock processes in SNRs and the role which supernovae play in forming stars.

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REFERENCES

Assousa, G. E., and Herbst, W. 1980, in *Giant Molecular Clouds in the Galaxy*, ed. P. M. Solomon and M. G. Edmunds (Oxford: Pergamon Press), p. 275.
Beichman, C. A., Neugebauer, G., Habing, H. J., Clegg, P. E., and Chester, T. J. 1984, *Infrared Astronomical Satellite Catalogs and Atlases, Explanatory Supplement* (Washington: U.S. Government Printing Office).
Blitz, L., Fich, M., and Stark, A. A. 1982, *Ap. J. Suppl.*, **49**, 183.
Braun, R., and Strom, R. G. 1985, *Astr. Ap.*, submitted.
Cornett, R. H. 1977, Ph.D. thesis, University of Maryland.
DeNoyer, L. K. 1979, *Ap. J.* (*Letters*), **232**, L165.
DeNoyer, L. K., and Frerking, M. A. 1981, *Ap. J.* (*Letters*), **246**, L37.
Dickinson, D. F., Kuiper, E. N. R., Dinger, A. S. C., and Kuiper, T. B. H. 1980, *Ap. J.* (*Letters*), **237**, L43.
Huang, Y.-L. 1985, Ph.D. thesis, Columbia University.
Keene, J., Davidson, J. A., Harper, D. A., Hildebrand, R. H., Jaffe, D. T., Loewenstein, R. F., Low, F. J., and Pernic, R. 1983, *Ap. J.* (*Letters*), **274**, L43.
Odenwald, S. F., and Shivanandan, K. 1985, *Ap. J.*, **292**, 460.
Öpik, E. G. 1953, *Irish Astr. J.*, **2**, 219.
Scoville, N. Z., Irvine, W. M., Wannier, P. G., and Predmore, C. R. 1977, *Ap. J.*, **216**, 320.
Wootten, H. A. 1978, Ph.D. thesis, The University of Texas at Austin.

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