DETECTION OF STAR FORMATION REGIONS NEAR SUPERNOVA REMNANT W44*

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Abstract. Observations of two infrared objects embedded in molecular clouds near the supernova remnant W44 are presented. W44-IRS1 offers compelling evidence that it is a star whose formation was recently induced by expansion of the supernova remnant. W44-IRS2 lies beyond the remnant, possibly apart from the region of its influence.

1. Introduction

To establish a causal relationship between supernovae and star formation requires a careful scrutiny of available data since supernova remnants and young stars are constituents of the same short-lived population of galactic objects. Being members of the same population, they inhabit similar restricted regions of the galactic disk, such as spiral arms. In fact, supernova remnants are frequently found in association with H II regions; of the twenty-three optical supernova remnants listed by van den Bergh *et al.* (1973), at least eleven are accompanied by H II regions. The discovery of young stars in the environment of a supernova remnant does little to establish a cause and effect relationship between the supernova and star formation in the same region.

Very young stars display characteristic radio and infrared spectra (Wynn-Williams, 1977); they are embedded in dense molecular clouds for which they may provide a heating source (Goldreich and Kwan, 1974), if of sufficient luminosity. In fact they are frequently first located via a careful infrared search of hot regions in molecular clouds (Blair *et al.*, 1975). If supernova remnants induce star formation, then molecular clouds containing photostars should be located in the vicinity of moderately old but well-established supernova remnants. Furthermore because in most molecular clouds the $J = 1 \rightarrow 0$ line of ^{12}CO is saturated at the kinetic temperature of the cloud, it is easily mapped and the dynamics of the interaction of the cloud with a supernova remnant explored. While the causal character of the relationship between the supernova remnant and star formation may still be difficult to prove, its plausibility can be enhanced by the detection of objects displaying characteristically protostellar infrared spectra and which are embeeded in dense molecular clouds which are demonstrably interacting with a well-established supernova remnant. We have studied molecular clouds in the vicinity of the

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well-known supernova remnants W44 (Wootten, 1977a), W28 (Wootten, 1977b), S147, and the Monoceros remnant. In this paper we present new results of an infrared survey of molecular clouds in the vicinity of W44.

2. Observations

Molecular line observations of the dense clouds have been made with the 4.9 m antenna of the Millimeter Wave Observatory (MWO)* at Fort Davis, Texas. The data reported here were taken at various times during 1976. Details of the observations are similar to those reported in Wootten (1977a).

Infrared observations from 1.2 to 3.6 μm were made with the InSb photometer on the 1.3 m telescope at Kitt Peak National Observatory in May 1976, using procedures similar to those reported in Evans *et al.* (1977). Data extending to 20 μm were obtained by Evans and Nadeau (private communication) on the Mt. Wilson 1.5 m telescope. Equipment and techniques were described by Beckwith *et al.* (1976).

3. Results

The major CO cloud associated with W44 has been discussed by Wootten (1977a) and by Dickel *et al.* (1976), and major features of its structure and interaction with the remnant are presented in detail in those references. In this paper we concentrate on infrared objects found in this and related clouds and their immediate surroundings.

Two objects possessing spectral features usually found in protostellar objects are of particular interest. Their positions and associated molecular clouds are shown in Figure 1.

3.1. W44IRS1

A small radio source (PKS1855 + 015) is present in numerous maps of this region, located at the periphery of the shell of the supernova remnant. Measurements of the spectrum of this source are collected in Table I. It is unresolved ($\leqslant 3'$) and its spectrum rises steeply toward higher frequencies, a characteristic of optically thick compact H II regions frequently associated with infrared objects embedded in molecular clouds. An infrared object and a molecular cloud have been found to coincide with this radio source (Figure 1). Infrared photometry of the object is reported in Table I.

CO emission from this region is complex. The molecular cloud enveloping W44 extends up to and beyond PKS1855 + 015, as does the H I cloud (Knapp and Kerr, 1974) in which dynamical effects of the supernova remnant are traceable to well beyond the continuum remnant. A component of the CO cloud at $V_{\mathrm{LSR}} \simeq 49.8 \mathrm{~km~s}^{-1}$ reaches its intensity maximum at the location of PKS1855 + 015 and is probably associated with it. The column density of ^{13}CO reaches its maximum value $n_{13}L = 2.2 \times 10^{16} \mathrm{~cm}^{-2}$ at the

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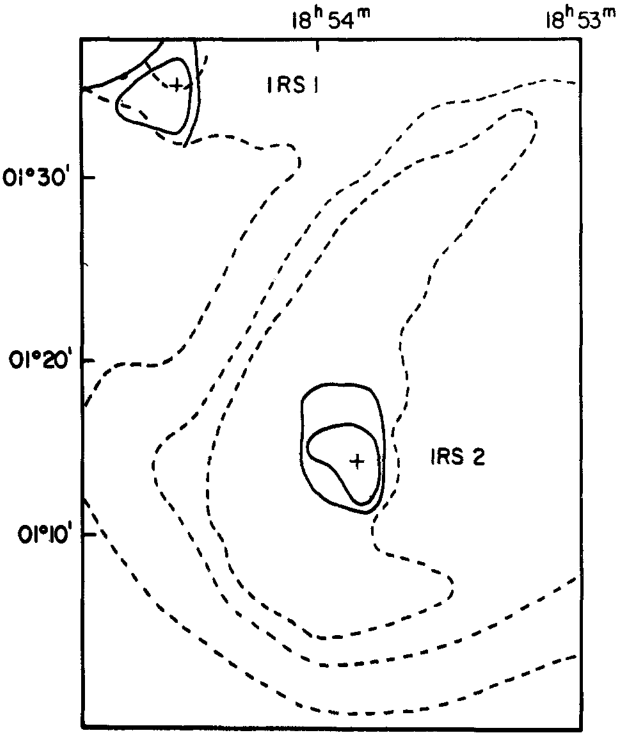

Fig. 1. Dashed lines are representative contours from 10.7 GHz continuum map of W44 by Kundu and Velusamy (1972). The locations of IRS1 and IRS2 are indicated by crosses. Contours of ^{13}CO emission from their associated molecular clouds are also shown; contour levels are $T_A^*(^{13}CO) = 3^\circ.5$ and $2^\circ.5$ for the IRS1 molecular cloud and $T_A^*(^{13}CO) = 2^\circ$ and 1° for the IRS2 molecular cloud.

position of the radio object, from which we infer that the gas density is highest in this region. The diameter of the molecular cloud, defined as the full width to half maximum intensity of ^{13}CO emission is $L \sim 3'$, or 10^{19} cm at the 3.5 kpc distance of W44. The average volume density and mass of a spherical cloud of this dimension are $n_{H_2} \simeq 10^3$ cm^{-2} and $M_c = 900 M_\odot$ assuming $n(^{13}CO)/n(H_2) \simeq 2 \times 10^{-6}$ (Dickman, 1975).

Similar complexes of a compact H II region, infrared source, and molecular cloud are found in regions of recent star formation (Wynn-Williams, 1977). We believe that the objects discussed here are manifestations of recent star formation and propose the following model: IRS1 is a star or 'protostar' recently formed from the molecular cloud for which it provides a heating source ($T_K = 15$ K). The compact H II region PKS1855 + 015 is probably excited by IRS1. All three objects are a fragment of a more massive molecular cloud which is interacting with W44. This interaction with the supernova remnant could have triggered the formation of IRS1. If this model is correct, W44IRS1 is the youngest and clearest example of supernova-induced star formation known.

Further observations are needed to test this model. A recent attempt to detect H85α emission from PKS1855 + 015 was unsuccessful; a comparison of recombination line

TABLE I

Observational data

A. PKS1855 + 015 ($\alpha = 18^h54^m33^s$. $\delta = 01° 34' 00''$. (1950))[a]

ν(Hz)	$S_\nu(Jy)$	Beam size	Reference
4.08×10^8	$\leqslant 0.5$	4′	Clark *et al.* (1975)
5.00×10^9	1.3	4′	Baker *et al.* (1973)
1.07×10^{10}	5.1	3′	Kundu and Velusamy (1972)

B. W44IRS1 ($\alpha = 18^h54^m31^s$. ± 16″ $\delta = 01° 34' 34''$. ± 16″ (1950))

$\lambda(\mu m)$	$S_\nu^b(Jy)$	Beam size
2.2	0.21 (.01)	16″
1.65	0.051 (.005)	16″
1.2	$\leqslant 2.4 \times 10^{-3}$ (3σ)	16″

[a] From Baker *et al.* (1973)
[b] 1σ errors given in parentheses

velocities with those of the molecular material could establish their relationship. Infrared observations are planned to estimate the luminosity of IRS1. This could be compared with the excitation requirements of PKS1855 + 015. Higher resolution radio observations are also needed.

3.2. W44IRS2

A much higher velocity CO cloud ($V_{LSR} = 82\,km\,s^{-1}$) than the one discussed above occurs near the peak non-thermal emission region of W44. At the column density and intensity peak of this cloud (Figure 1) a bright infrared source has been discovered. Observations of this object have been extended to 20 μm (Figure 2) by Evans and Nadeau (private communication). The energy distribution is similar to that of 'protostellar' sources embedded in molecular clouds (Wynn-Williams, 1977); the color temperature of the source determined from 12.5 μm and 3.4 μm photometry is $T_c \sim 620\,K$ and an absorption feature at 10 μm is apparent.

The relationship of the molecular cloud and infrared source to W44 is shown in Figure 1. The column density determined from ^{13}CO observations is $n_{13}L = 7 \times 10^{15}\,cm^{-2}$. Because no material is seen in absorption against the remnant at the CO velocity at this position (cf. references in Wootten, 1977a) the cloud must lie beyond the remnant. We consider two possible locations: (a) the cloud is located just beyond the remnant at 3.5 kpc and its velocity is a result of expansion of the remnant, and (b) the cloud is located at its kinematic distance of 6 kpc well beyond the influence of the remnant. If the cloud is located at distance (a) its mass can be estimated from its area and total column density resulting in $M_c \simeq 7 \times 10^2 M_\odot$. If it has been swept from an ambient medium at $V_{LSR} \simeq 50\,km\,s^{-1}$ its velocity has been increased by $\sim 30\,km\,s^{-1}$ and the momentum in the cloud is $3 \times 10^{42}\,g\,cm\,s^{-1}$. This is comparable to the momentum

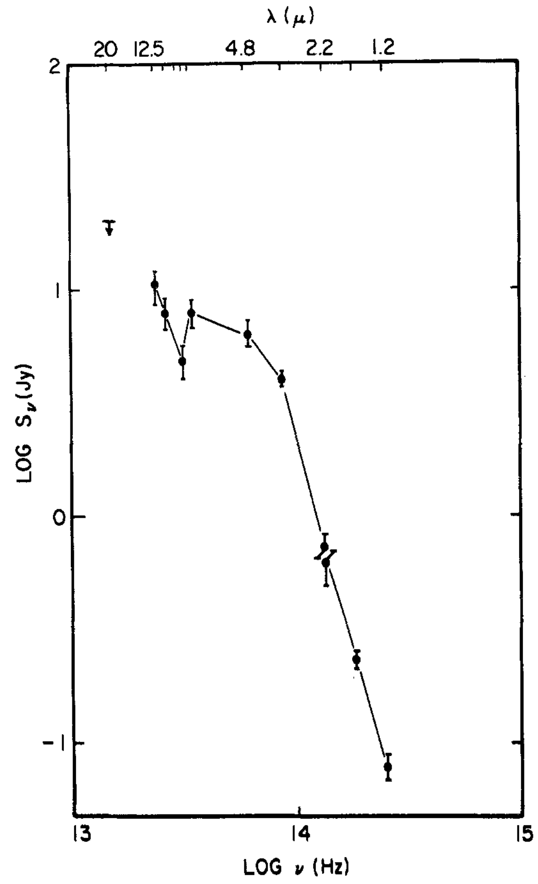

Fig. 2. The infrared spectrum of W44IRS2 ($\alpha = 18^h53^m53^s$. $\delta = +01° 15' 15''$ (1950)). Photometry at 2.2, 1.65 and 1.2 μm was obtained at Kitt Peak; photometry at other wavelengths was obtained at Mt. Wilson by Evans and Nadeau (private communication). A 15″ aperture was used for the Kitt Peak observations, and 9″ for the Mt. Wilson Observations.

contained in the entire H I shell of HB21 (Assousa and Erkes, 1973). It seems unlikely that so much momentum could be imparted to a region covering less than 3% of the total surface area of the remnant. Therefore distance (b) may be correct. In this case the cloud mass is $M_c \simeq 2 \times 10^3 M_\odot$ and the luminosity of the infrared source $L_s = 1.5 \times 10^4 L_\odot$ from 1–20 μ uncorrected for silicate absorption.

These observations indicate that W44IRS2 is heating a molecular cloud located beyond the supernova remnant perhaps at a distance of 6 kpc.

4. Conclusions

An infrared survey of portions of the molecular cloud associated with the supernova remnant W44 has been made in an attempt to find very young examples of supernova induced star formation. Two objects have been found which appear to be quite young; W44IRS1 is almost certainly associated with W44. This object coincides with a compact thermal source which appears to be optically thick at frequences up to 10.7 GHz and with a fairly massive ($900 M_\odot$) fragment of the molecular cloud which is interacting with the supernova remnant W44. These data indicate that W44IRS1 is an example of a star observed just after its formative stages. Furthermore, it is in close proximity to a supernova remnant which is expanding into the dense material surrounding the star. The possibility that the formation of this star was triggered by expansion of the supernova remnant into a molecular cloud is attractive.

W44IRS2 is the brighter of the two objects, but is associated with a molecular cloud whose association with W44 is uncertain. Two distances are possible; momentum arguments seem to favor a location more distant than W44. Until the distance ambiguity can be resolved W44IRS2 is a weaker candidate than IRS1 for an example of supernova-induced star formation.

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References

Assoussa, G.E. and Erkes, J.W.: 1973, *Astron. J.* 78, 885.
Baker, J.R., Preuss, E., and Whiteoak, J.B.: 1973, *Astrophys. J. (Letters)* **14**, 123.
Beckwith, S., Evans, N.J., II, Becklin, E.E., and Neugebauer, G.: 1976, *Astrophys. J.* **208**, 390.
Blair, G.N., Peters W.L., and Vanden Bout, P.A.: 1975, *Astrophys. J. (Letters)* **200**, L161.
Clark, D.H., Green, A.J., and Caswell, J.L.: 1975, *Aust. J. Phys. Suppl.* **37**, 75.
Dickel, J.R., Dickel, H.R., and Crutcher, R.M.: 1976, *Publ. Astron. Soc. Pacific* **88**, 840.
Evans, N.J., II, Blair, Guy, N., and Beckwith, S.: 1977, *Astrophys. J.* **217**, 448.
Goldreich, P. and Kwan, J.: 1974, *Astrophys. J.* **189**, 441.
Knapp, G. R. and Kerr, F. J.: 1974, *Astron. Astrophys.* **33**, 463.
Kundu, M.R. and Velusamy, T.: 1972, *Astron. Astrophys.* **20**, 237.
van den Bergh, S., Marscher, A.P., and Terzian, Y.: 1973, *Astrophys. J. Suppl.* **26**, 19.
Wootten, H. Alwyn: 1977a, *Astrophys. J.* **216**, 440.
Wootten, Alwyn: 1977b, *Bull. AAS* 9, 589.
Wynn-Williams, C.G.: 1977, in *Star Formation* (T. de Jong and A. Maeder eds.). Reidel, Dordrecht, p. 119.