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A LARGE MOLECULAR CLOUD TOWARD THE SNR W50 AND SS 433

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ABSTRACT

The CO $1 \rightarrow 0$ transition at 115 GHz has been mapped over an area of more than 6 deg^2 toward W50, the extended SNR surrounding the peculiar object SS 433 ($l = 39°.7$, $b = -2°.3$). W50 is found to lie at the end of a filamentary molecular cloud 4° long and 1° wide that closely matches a conspicuous dust lane on the Palomar Sky Survey; the cloud's kinematic distance is 2.2 ± 0.7 kpc, in agreement with the distance 2–3.3 kpc estimated for the SNR, and its mass is about 1.2×10^5 $M_{\odot}$. Though there is little evidence of star formation in the molecular filament, or evidence of an interaction between the filament and W50 (or SS 433), the positional coincidence of the two, their similar distance, and their displacement nearly two molecular scale heights from the plane all suggest a physical relationship or common origin. One possibility is that both the molecular filament and the stellar progenitor of W50 were ejected from a large active molecular complex lying in the plane at $l = 40°$.

Subject headings: interstellar: molecules — nebulae: individual — nebulae: supernova remnants

I. INTRODUCTION

If Type II supernovae as generally thought result from the detonation of massive, short-lived stars born in molecular clouds, it ought to be possible to observe a correlation in position between supernova remnants and molecular clouds, and even to identify the parent clouds of some remnants. Within 4 kpc of the solar system, seven examples of an association between a SNR and a molecular cloud have already been proposed (Table 1); we wish here to propose an eighth: a cloud in the direction of the old remnant W50 surrounding the remarkable object SS 433. Our search toward W50 for molecular gas with the CO $1 \rightarrow 0$ transition at 115 GHz was prompted by a conspicuous finger of dark nebulosity on the Palomar Sky Survey pointing obliquely down from the galactic plane to W50. As Figure 3 shows, the outline of the molecular cloud we have detected matches this dark nebula in considerable detail.

Because of its apparent association with SS 433 (cf. Beer 1981), W50 has recently been studied at high angular resolution in the radio continuum (Geldzahler, Pauls, and Salter 1980; Downes, Pauls, and Salter 1981). The 2.7 GHz map by Downes *et al.* shows the SNR to be a roughly spherical shell with extensions to the east and west, containing a point source at the position of SS 433 (Fig. 1) which is so near the center that Ryle *et al.* (1978) proposed it as the stellar remnant of the supernova explosion. In Shaver's (1982) survey of SNRs, W50 is the most flattened object, and it has been suggested that this flattening is the result of the high-velocity expulsion of material from SS 433 (e.g., Seward *et al.* 1980).

II. OBSERVATIONS

Our observations of the vicinity of W50 were made with the 1.2 m millimeter-wave telescope at Columbia University whose Cassegrain antenna has a half-power beamwidth of 8′ and a beam efficiency of 0.79 at 115 GHz, the frequency of the CO $1 \rightarrow 0$ transition. Its spectrometer is a filter bank of 256 channels each 250 kHz wide, providing at 115 GHz a velocity resolution of 0.65 km s^{-1}. Spectra were taken by position switching with a period of 30 s between the source position and a nearby reference position free of CO emission, until the rms channel-to-channel noise was about 0.3 K and lines as weak as 1 K could easily be measured. A typical observation required 10 minutes. Calibration of the 1.2 m telescope is done with a standard room temperature blackbody chopper wheel that automatically corrects for atmospheric attenuation; the line intensity given here has in addition been corrected for beam efficiency to yield the radiation temperature T_R (related to the radiation intensity I_ν by the Rayleigh-Jeans formula $I_\nu = 2kT_R/\lambda^2$).

A total of 304 positions was observed over an area of 6 deg^2 (Fig. 2), the dust lane being sampled every beamwidth in l and b. Observations of the $1 \rightarrow 0$ transition of ^{13}CO at 110 GHz were also made in a limited region near the most intense CO emission. Figure 2, a contour map of the radiation temperature at the line peak, and Figure 3, a similar map of the velocity-

TABLE 1

SNRs WITHIN 4 kpc OF THE SUN POSSIBLY ASSOCIATED WITH MOLECULAR CLOUDS

SNR	l	b	r(kpc)	References
W28	6.4	−0.1	1.8	1
W44	34.6	−0.5	3.0	2, 3
W50	39.7	−2.3	2.0–3.3	4
Cygnus Loop	74.0	−8.6	3.3	5
CTB 109	109.1	−1.0	4.0	6
Cas A	111.7	−2.1	3.3	7
IC 443	189.1	+2.9	1.5	5, 8
Monoceros Loop	205.5	+0.2	1.3	9

REFERENCES.—(1) Wootten 1981. (2) Wootten 1977. (3) Dame 1983. (4) This work. (5) Scoville *et al.* 1977. (6) Heydari-Malayeri *et al.* 1981. (7) Cohen *et al.* 1980. (8) Cornett *et al.* 1977. (9) Wootten 1978.

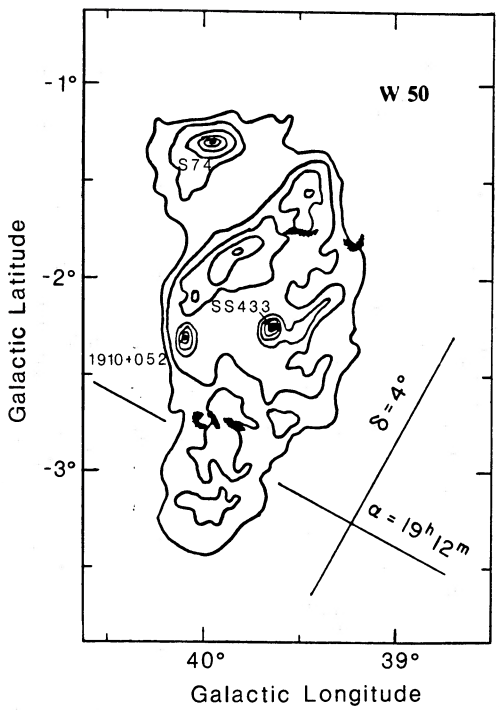

FIG. 1.—A simplified version of the 2.7 GHz map of W50 from Downes *et al.* (1981). The optical filaments (van den Bergh 1980; Zealey *et al.* 1980) are indicated by the hatched lines. The compact source 1910+052 is extragalactic (van Gorkom *et al.* 1982). The H II region S74 may be an unrelated background object if W50 is at 2.2 kpc (Blitz, Fich, and Stark 1982).

integrated intensity $W_{CO} = \int T_R \, dv$, summarize the CO data.

III. DISCUSSION

Using the rotation curve of Burton and Shane (1970), the galactocentric distance of the W50 molecular cloud calculated from our data is 8.4 kpc, and its heliocentric distance r is either 2.2 or 13.2 kpc. At the far distance it is highly unlikely that the cloud would be visible on the Palomar plate, and furthermore it would be more than 500 pc below the galactic plane—over eight times the molecular cloud scale height of 60 pc measured by galactic CO surveys (e.g., Cohen and Thaddeus 1977). It must therefore be at the near distance, which at a galactic longitude of 40° places it in the near side of the Sagittarius arm. Possible random and streaming motions of order 10 km s^{-1} superposed on the galactic rotation make this kinematic distance uncertain by 30%, so we conclude that $r = 2.2 \pm 0.7$ kpc. Recent estimates of the distance to W50 based mainly on the Σ-D relation lie as Table 2 shows in the range 2–3.3 kpc.

Though there is little evidence in our data for interaction between W50 and its apparent molecular cloud companion, such as has been claimed for some of the remnants in Table 1 (e.g., W28, W44), it is easy to show that some relation between the two is likely to exist. A simple calculation indicates that the probability of achieving by chance the coincidence in position and velocity that we observe is at most a few percent, and it is therefore plausible that the stellar progenitor of W50 and SS 433 formed in this molecular cloud, or that both had a common origin. In view of the large distance to the W50 cloud, the close correspondence between the dark nebula and the CO emission is remarkable (see Fig. 3). The molecular cloud is perhaps the most distant cloud which can be seen so clearly as a dark nebula. This distinction is probably a result of its favorable location: far enough from the plane to avoid the local obscuration in the Great Rift but close enough to the plane to be silhouetted against the distant stellar disk.

Since the SNR W50 lies in the vicinity of a spiral-arm molecular cloud, it seems likely that it is the result of a Type II supernova (Huang, Dame, and Thaddeus 1982). Although no evidence of massive-star formation has been found in this region this may be largely due to its

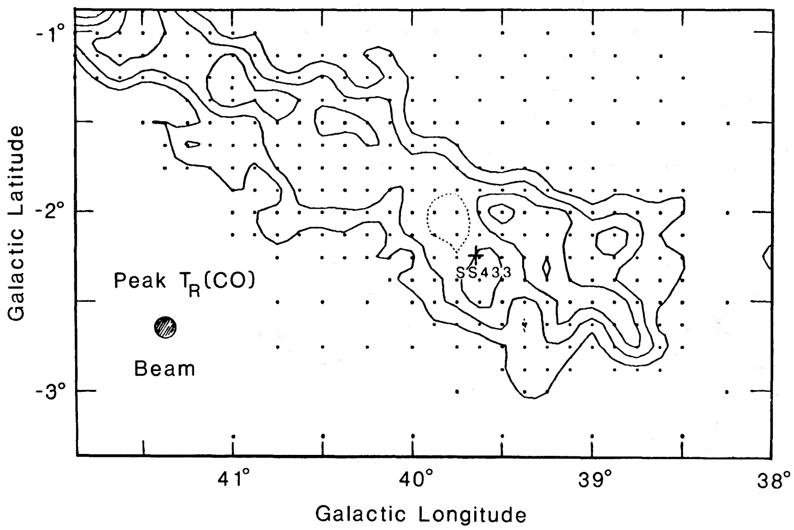

FIG. 2.—Map of the peak CO radiation temperature in the LSR velocity range 27–36 km s^{-1} in the vicinity of W50. The contour interval is 0.75 K. Dots indicate positions observed. Contours enclosing depressions (down-going contours) are dotted.

large distance. A detailed investigation of the region for signs of star formation would be of interest.

A low resolution (1°) galactic CO survey by Dame and Thaddeus (1983) shows that the W50 cloud is apparently an extension of a large CO complex in the galactic plane also at $V_{\rm LSR} = 32$ km s^{-1}. The 21 cm survey of Weaver and Williams (1973) also shows enhanced emission at that velocity in this region, suggesting that the entire CO complex may be embedded in an even larger H I halo. A sketch of these objects is given in Figure 4.

The mass of a molecular cloud may be estimated in several ways: from the velocity-integrated CO intensity, from the LTE ^{13}CO column density $N(^{13}\rm CO)$, from the visual extinction, and from the virial theorem. Each of these methods has been applied and is briefly discussed below.

An empirical value for the ratio of the molecular hydrogen column density $N(\rm H_2)$ to the velocity-integrated CO $1 \rightarrow 0$ line intensity $W_{\rm CO}$ has recently been derived by Lebrun *et al.* (1983) by comparing the distribution of γ-rays measured by *COS B* in the first galactic quadrant to that of H I and CO. They find:

$$N(\mathrm{H}_2)/W_{\mathrm{CO}} = 2\times 10^{20}\ \mathrm{cm}^{-2}/(\mathrm{K\ km\ s}^{-1}), \quad (1)$$

with an uncertainty of roughly a factor of 2. This ratio is consistent with the approximately linear relation that exists between $N(^{13}\rm CO)$ and $W_{\rm CO}$ (Dickman 1978), if 5×10^5 is adopted for the ratio $N(\mathrm{H_2})/N(^{13}\mathrm{CO})$. Taking 2.36 for the mean molecular weight, the mass of the W50 cloud is found in this way to be $1.2\times 10^5\ M_\odot$.

The $1 \rightarrow 0$ transition of ^{13}CO was only observed at 51 positions in the W50 cloud, and it is not possible with this data to determine reliably the mass of the entire filament, but it is possible to check the $\rm H_2$ column density at those positions in the LTE approximation (e.g., cf. Dickman 1975). At the 18 positions where ^{13}CO lines were detected, the average $\rm H_2$ column density is found to be 1.6×10^{21} cm^{-2}, in agreement with that calculated from $W_{\rm CO}$ to within ~ 30%.

Since the star counts are not available over the total area of the cloud, a reliable total mass could not be deduced from the visual extinction. However, Dickman (1982) has derived a mean extinction of 1–2 mag from star counts at about 10 positions within the cloud, in good agreement with the 1.6 mag of extinction implied by the average $\rm H_2$ column density we find from the gas to extinction ratio of Bohlin, Savage, and Drake (1978).

The CO velocity structure of the W50 molecular cloud is shown in Figure 5. There is no significant velocity gradient along its major axis, but a distinct gradient of 4 km s^{-1} deg^{-1} exists along its minor axis, suggesting that the cloud may be a cigar-shaped object slowly rotating about its long axis with a period of ~ 10^8 yr. The virial mass $M_{\rm vir}$ obtained when such a model is applied to the observed CO linewidth and velocity structure constitutes an upper limit to the cloud mass, and serves as a check on the mass derived from the ^{12}CO and ^{13}CO intensities. For a uniform density prolate spheroid

$$M_{\rm vir} = \frac{5c\,\Delta v^2}{(4\ln 2)G}\ \frac{e}{\ln\left(\dfrac{1+e}{1-e}\right)}$$

$$= 2.3\times 10^5\ M_\odot, \quad (2)$$

where $e = (1 - a^2/c^2)^{1/2}$ is the spheroid's eccentricity,

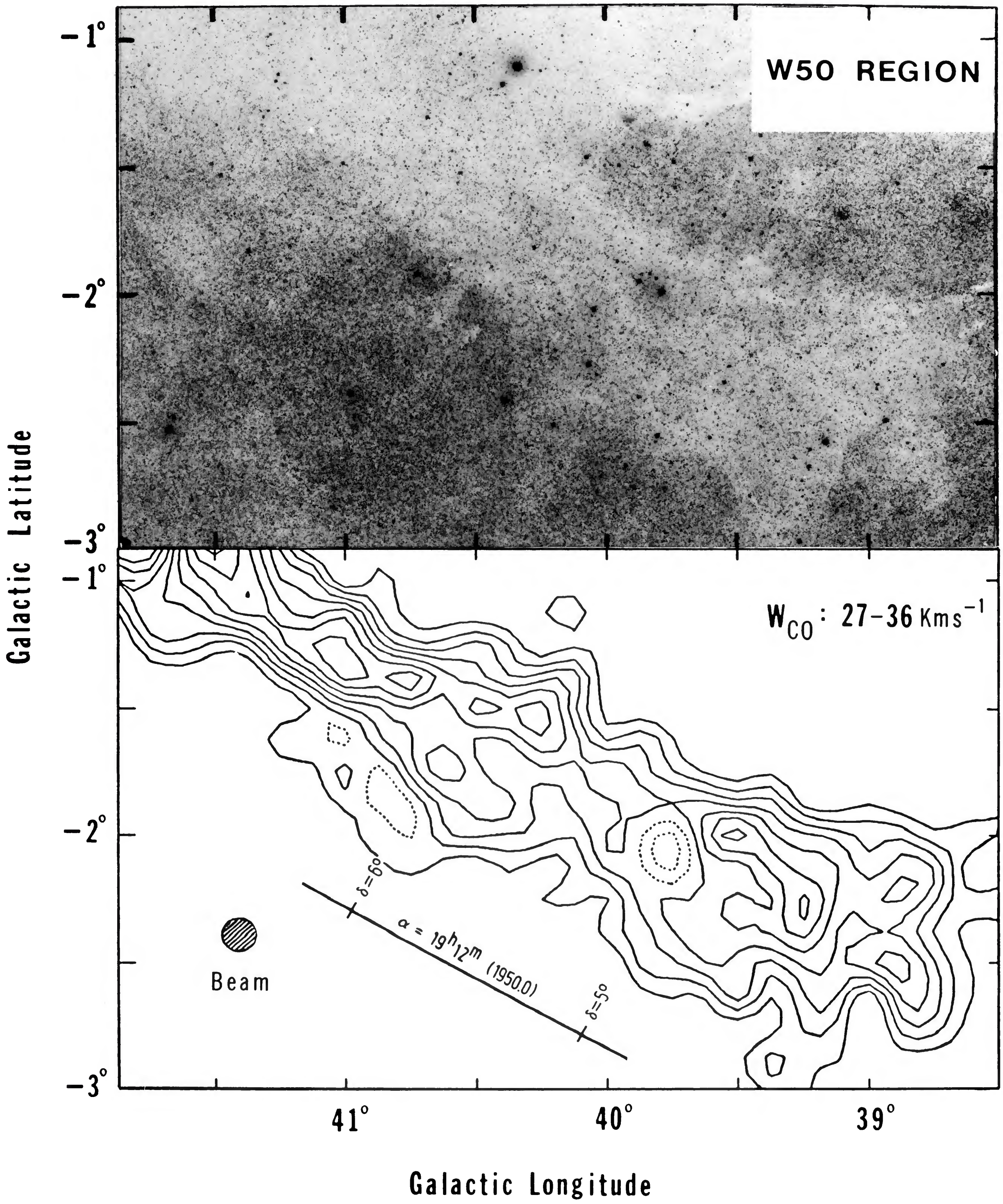

FIG. 3.—Map of the velocity-integrated CO intensity compared with the red print of the Palomar Sky Survey. The contour interval is 2 K-km s^{-1}. The heavy extinction near the galactic plane has a CO counterpart in local velocity gas below the velocity range of this figure and hence not shown. Contours enclosing depressions (down-going contours) are dotted.

TABLE 2

ESTIMATES OF THE DISTANCE TO W50

Distance (kpc)	Source
3.3	Ryle *et al.* 1978
2.2	Milne 1979
3.3	Caswell and Lerche 1979
< 3.3	van den Bergh 1980
2.0–3.2	Geldzahler *et al.* 1980
2.6 ± 0.3 ...	Crampton 1980
> 2.3	Downes *et al.* 1981

$a = 15$ pc its semiminor and $c = 70$ pc its semimajor axis, and $\Delta v = 6$ km s^{-1} is the full velocity width at half-intensity of the "composite" CO line—the line obtained by summing all the data that would be observed by an antenna whose beam is larger than the cloud, on the assumption that the line shape is Gaussian.

IV. SUMMARY

1. A dark dust lane on the Palomar Sky Survey toward W50 and SS 433 corresponds to a filamentary

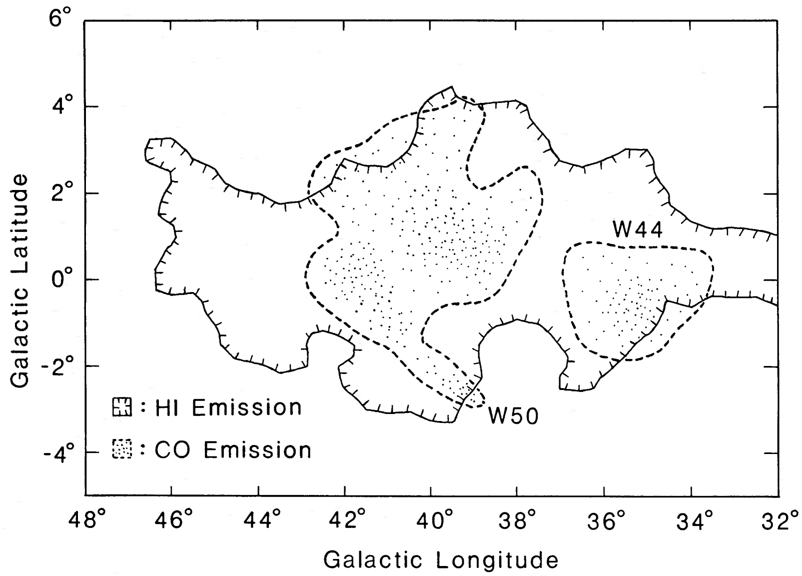

FIG. 4.—Large-scale structure in the integrated intensity of CO and H I in the near Sagittarius arm in the vicinity of $l = 40°$. In CO the 2 K km s^{-1} contour and in H I the 440 K km s^{-1} contour are indicated, the integration in velocity in either case being from 27 to 36 km s^{-1}. In terms of column density, these contours correspond to 4×10^{20} H_2 molecules per cm^2 by eq. (1), and 8×10^{20} H atoms per cm^2 if the 21 cm line is optically thin.

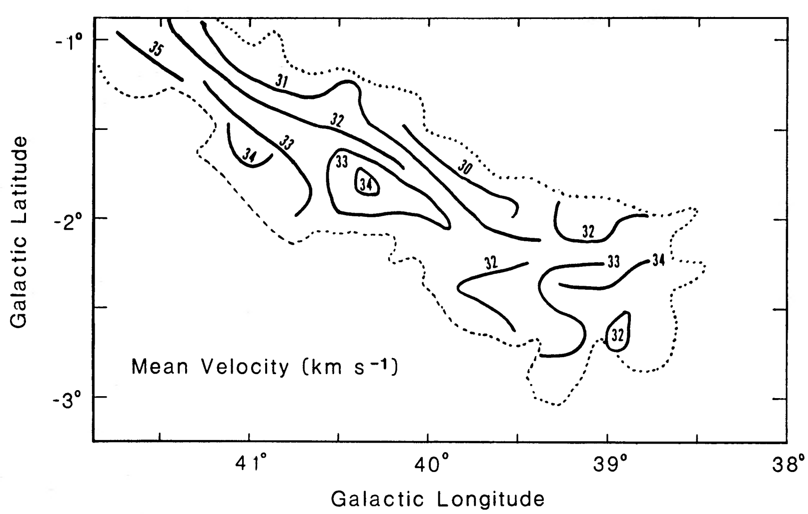

FIG. 5.—Velocity map of the W50 molecular cloud: contours of the mean CO velocities of the data in Fig. 3. Dashed line is the lowest contour in Fig. 3.

molecular cloud extending downward from a large molecular complex in the galactic plane.

2. The kinematic distance of the W50 cloud, 2.2 ± 0.7 kpc, places it in the near Sagittarius arm. This distance agrees with that to W50 and SS 433 to within the observational uncertainties.

3. Although there is no obvious evidence of interaction, it is statistically improbable that W50 and its molecular companion are unrelated objects.

4. The mass of the W50 molecular cloud is estimated by several methods to be about $1.2 \times 10^5 \ M_\odot$.

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