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Star Formation in Carina OB1: Observations of a Giant Molecular Cloud Associated with the η Carinae Nebula

D.A. Grabelsky,[1,2] R.S. Cohen,[1] and P. Thaddeus[1,3]
[1]Columbia University, Department of Astronomy, New York, NY
[2]Northwestern University, Dept. of Physics and Astronomy, Evanston, IL
[3]Goddard Institute for Space Studies, 2880 Broadway, New York, NY

ABSTRACT. A giant molecular cloud associated with the η Carinae nebula has been fully mapped in CO with the Columbia Millimeter-Wave Telescope at Cerro Tololo. The cloud complex has a mass of roughly 7 x 10^5 $M_\odot$ and extends about 140 pc along the Galactic plane, with the giant Carina HII region situated at one end of the complex. Clear evidence of interaction between the HII region and the molecular cloud is found in the relative motions of the ionized gas, the molecular gas, and the dust; simple energy and momentum considerations suggest that the HII region is responsible for the observed motion of a cloud fragment. The molecular cloud complex appears to be the parent material of the entire Car OB1 Association which, in addition to the young clusters in the Carina nebula, includes the generally older clusters NGC 3324, NGC 3293, and IC 2581. We estimate the overall star formation efficiency in the cloud complex to be ~0.02.

1. INTRODUCTION

The η Carinae nebula (NGC 3372) is among the brightest giant HII regions in the Galaxy, and the young clusters that supply the ionizing radiation -- Tr 14, Tr 16, and Cr 228 -- comprise one of the largest known Galactic concentrations of massive stars: 16 main sequence O stars, including 5 classified O3V (Walborn 1971, 1973). Interstellar absorption lines observed toward many of the member stars display velocities ranging over 550 km s^{-1} (Walborn 1982), and it is generally agreed that the Carina nebula is pumping a lot of energy into the surrounding medium. Within about 2^o along the Galactic plane lie the three somewhat older and less spectacular clusters NGC 3324, NGC 3293, and IC 2581, which, together with the clusters in the Carina nebula, make up the Carina OB1 Association.

Because it lies in the Southern skies, CO observations of the region in and around the Carina nebula were, until recently, limited either to single detections (Gillespie *et al.* 1977; White and Phillips 1983) or to small region mapping (de Graauw *et al.* 1981). In 1983 we installed the Columbia Southern Millimeter-Wave Telescope at Cerro Tololo and carried out the first well-sampled CO survey of the entire Southern Milky Way. As part of that survey, we mapped a large molecular cloud complex that is the parent material of the Car OB1 Association. In this paper we present the observations of the η Carinae molecular cloud complex, point out the interesting dynamical relationship between the molecular cloud and the HII region, and give an estimate of the overall star formation efficiency in the molecular cloud.

2. OBSERVATIONS

The CO observations were made between 1983 January and November at Cerro

Tololo with the Columbia Southern Millimeter-Wave Telescope (Grabelsky 1985; Bronfman 1986). The telescope has a beamwidth of 8.8′ at 2.6 mm, and its pointing accuracy is better than 1′. The detection system consists of a liquid nitrogen cooled superheterodyne receiver with a single-sideband noise temperature of ~380 K, and a filterbank spectrometer with 256 channels, each 1.3 km s^{-1} wide at 2.6 mm for a total bandwidth of 333 km s^{-1}. Spectra were calibrated against a blackbody reference following the standard chopper wheel technique (Kutner 1978), and only linear baselines were subtracted. Integrations times were typically 5 minutes, yielding an rms noise per channel of ~0.14 K.

The region in and around the Carina nebula was covered in a survey of molecular clouds in the Carina spiral arm (Grabelsky 1985). Observations were space every 1/8° in *l* and b in the range $270° \leq l \leq 300°$, $|b| \leq 1°$, with latitude extensions as needed to cover all nonlocal emission. The spectrometer bandwidth, centered at v = 0, was more than adequate to cover all Galactic plane emission within the longitude range of the survey.

3. IDENTIFICATION OF THE CLOUD COMPLEX

A mosaic of ESO J plates showing the η Carinae nebula and its surroundings is displayed in Figure 1; the bright gas between $l = 287°$ and 288° is the Carina HII region. Although the young clusters in the Carina nebula are washed out in this photograph, the other Car OB1 clusters can be identified: IC 2581 (l,b = 284.7°,0.1°), NGC 3293 (285.9°,0.1°), and NGC 3324 (286.2°,-0.2°). Various published distances place these clusters, as well as the Carina nebula, at 2.7 kpc. The overlaid contours in Figure 1 show CO emission integrated over velocity from -50 to -9 km s^{-1}. Along the Galactic plane a sequence of molecular clouds from l,b = 285°,0° to 288°,-1° is evident. Each molecular cloud in the apparent grouping is physically related to one or more of the Car OB1 clusters, thus placing each cloud at the same distance and establishing the identity of the molecular cloud complex. In each case the evidence for the association of a cluster with a molecular cloud in the complex is the spatial proximity and similar velocities; cluster velocities were determined either from member stars or from associated HII regions. In the case of the Carina nebula, discussed in the next section, there is, additionally, clear evidence for direct contact between the HII region and the molecular cloud.

With the now widely-used assumption that integrated CO line temperature, denoted W(CO), is proportional to $N(H_2)$, the H_2 column density, and adopting the γ ray calibration of Bloemen *et al.* (1986) of the W(CO)-$N(H_2)$ relation, we obtained a mass of 6.7×10^5 $M_\odot$ for the entire molecular cloud complex. We call this the CO mass to indicate that it is based on W(CO). This value is within about a factor of two of the virial mass derived by assuming that the observed bulk motions in the complex support the cloud against gravity.

4. INTERACTION BETWEEN THE CLOUD AND THE HII REGION

One of the prominent features of the Carina nebula is the dark dust lane that crosses the face of the bright gas. The generally good spatial correlation between the CO and the dust suggests that a portion of the molecular cloud must lie in front of the HII region, while the coincidence of the strong CO peak at l,b = 287.5°,-0.5° with the bright gas indicates that

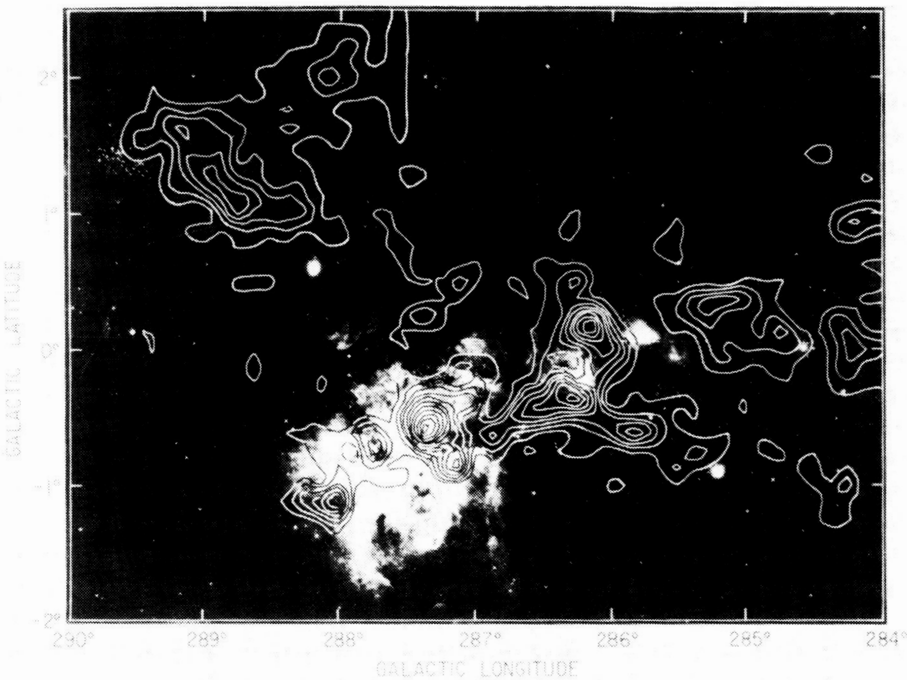

FIGURE 1. Mosaic of ESO J plates showing the η Carinae nebula and its surroundings. The overlaid contours show CO emission integrated over velocity from -50 to -9 km s^{-1}. The contour interval is 5 K km s^{-1}. Note the good correlation between the CO and the dust lanes in the vicinity of the bright gas. This dust represents a fragment of the molecular cloud that is being driven out by the HII region.

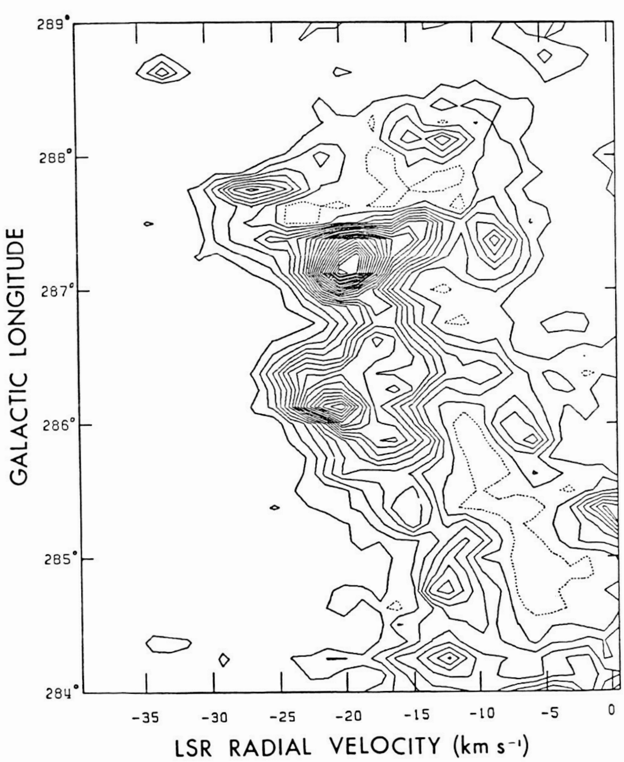

FIGURE 2. Longitude-velocity map of the η Carinae molecular cloud complex. The CO emission is integrated in latitude from b = -1^0 to 0^0; the contour interval is 0.125 K-deg. The mean velocity of the emission is -19 km s^{-1}, but near the longitude of the HII region ($l \approx 287.5^0$) a cloud fragment with a velocity of about -26 km s^{-1} is seen. This fragment or filament corresponds to the dust lane in front of the Carina nebula, and its appearance as a blue-shifted feature (relative to the mean cloud velocity) indicates that it is moving out from the main body of the cloud. The CO mass of the filament is ~2 x 10^4 $M_\odot$ and its velocity relative to the mean cloud velocity is 7 km s^{-1}. The HII region is evidently driving the filament outward.

much of the molecular cloud is located behind the HII region. A longitude-velocity map integrated from b = -1^0 to 0^0 is shown in Figure 2. The mean velocity of the cloud complex is -19 km s^{-1}, quite close to the mean HII region velocity of -20 km s^{-1}; but at the longitude of the Carina HII region there a CO "filament" with a velocity of about -26 km s^{-1}. This blue-shifted filament corresponds to the dust lane and the HII region may be driving the filament outward with a relative velocity of ~7 km s^{-1}. The spatial correlation of the blue-shifted CO filament and the dust lane is confirmed in spatial maps which sample narrow velocity "slices" through the cloud (not shown here).

To check whether the HII region could be the source of the filament's motion, we considered two possible mechanisms for driving the filament out from the main body of the cloud: a stellar wind-driven bubble, and the rocket effect. Following Castor *et al.* (1975), the velocity of the swept-up shell around a wind-driven bubble can be expressed $v_s = 2.7 \times 10^3 (\dot{M} v_w^2 n_o^{-1})^{1/5} t^{-2/5}$ km s^{-1}. With the assumption that the CO filament is a piece of swept-up shell and reasonable values in the Carina nebula for the stellar mass loss rate ($\dot{M}$), wind velocity, (v_w), ambient cloud density (n_o), and age (t), a stellar wind-driven bubble can easily account for the observed motion of the filament. Similarly, in the Carina nebula there is enough ionizing radiation to make the rocket effect of ionized gas streaming off the filament a plausible mechanism for accelerating the filament. Evidently, the HII region is severely disrupting the cloud.

5. STAR FORMATION EFFICIENCY

The star formation efficiency, SFE, is the ratio of stellar mass to total stellar plus molecular cloud masses. For the cloud mass we used the CO mass found above (§ 3.). To estimate the stellar mass we simply tallied up the mass in all the observed stars with spectral types earlier than B0.5, and used the IMF of Miller and Scalo (1979) to determine the total mass in spectral types B0.5 and later. The IMF was calibrated to the number of observed B0.5V stars. Our assumption that a reasonable total mass in early type stars can be attained by simply counting them is based on the unusually large number of early type stars observed in the Carina nebula. Using this method we obtained SFE = 0.02. This result is in good agreement with SFE determined by Myers *et al.* (1986) for about 50 inner-Galaxy giant molecular clouds.

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