THE DISRUPTION OF THE MOLECULAR CLOUD ASSOCIATED WITH THE NORTH AMERICA AND PELICAN NEBULAE

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Giant molecular clouds can be destroyed in several ways: by conversion of gas into stars; by dissociation of H_2 into HI; by ionization and formation of HII regions; and by dispersal of the cloud into cloudets. The relative importance of these processes can be assessed by observations of evolved HII regions and associated molecular clouds. A number of such complexes have been studied in ^{12}CO at the Five College Radio Astronomy Observatory (FCRAO) as part of an extensive investigation of clouds associated with about 60 Sharpless HII regions. A particularly clear example of cloud disruption is found in the case of W80, the North America and Pelican Nebulae in Cygnus (Bally and Scoville 1980).

The W80 HII region, located at a distance of roughly 1 kpc (Goudis 1976), is highly evolved,as indicated by the low mean electron density of $n_e \sim 9$ cm^{-3} (Wendeker 1968) and its large angular diameter of 50 pc. A fragmented molecular cloud is associated with this complex and is responsible for the foreground obscuration that separates the North America Nebula from the Pelican. The molecular gas in the northern half of the complex exhibits a systematic expansion away from the center of the HII region. All the CO emission from gas near the edge of the complex has a velocity close to $V_{LSR} = 0$ km s^{-1} while emission near the center exhibits line splitting with a peak to peak separation of 10 km s^{-1}. The negative velocity component correlates well with the foreground dust, hence must be gas in front of the HII region. The positive velocity component can be seen in the direction of Hα emission from the Pelican, thus must be emitted by gas behind the nebula. An overall picture of the kinematics of the CO surrounding the northern half of W80 is shown in Fig. 1 where the vertical axis represents distance from the centroid of the free-free emission. Clearly the gas can be characterized as an expanding molecular shell with an expansion velocity of v = 5 km s^{-1}. The very opaque gas in front of the southern portion of the N.A. Nebula which has $A_V \gtrsim 10$ mag. does not partake in the general expansion; evidently the column density of this gas is too great to be dynamically affected by the high pressure HII region.

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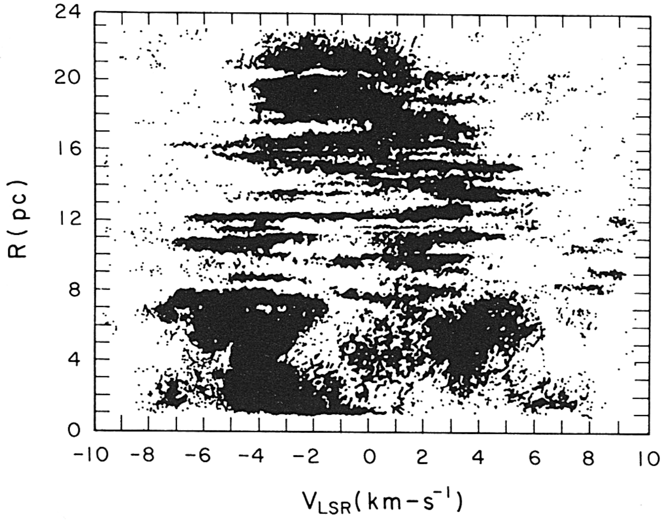

Fig. 1. A radius-velocity diagram of ^{12}CO emission in the northern half of W80 using 200 spectra. The vertical axis represents projected distance from the centroid of the free-free emission to each particular spectrum.

We have modeled the expanding shell surrounding W80 as the last phase in the evolution of the post-shock layer associated with the expansion of the HII region. Once an OB subgroup is born inside a molecular cloud the expansion of the high pressure HII gas sweeps up material behind a weak D-type shock front. Eventually the HII bubble reaches the nearest edge of the molecular cloud and bursts (Bodenheimer et al. 1979). Once the resulting rarefaction wave has reached the ionization front at the inner-edge of the HII cavity, a streaming HII region is established which continues to push the shock front further into the cloud. Eventually the shock runs through the back of the cloud and accretion by the post-shock layer ends. After this, the rocket effect (Oort and Spitzer 1954) can accelerate the shocked gas layer; Fig. 2 shows a schematic diagram of this evolutionary process. Model calculations for a homogeneous molecular cloud indicate that the current stage of evolution is reached between 3 to 6 million years after the onset of O & B star formation. The ionizing flux of 5×10^{49} photons s^{-1} has ionized about 2×10^4 $M_\odot$ of the original molecular cloud material. About 3-6 x 10^4 $M_\odot$ of gas has been accelerated by the rocket effect and will probably survive in molecular form. A piece of the cloud of $M \sim 3 \times 10^4$ $M_\odot$ in the southern portion of the complex has not yet been significantly affected by the HII region.

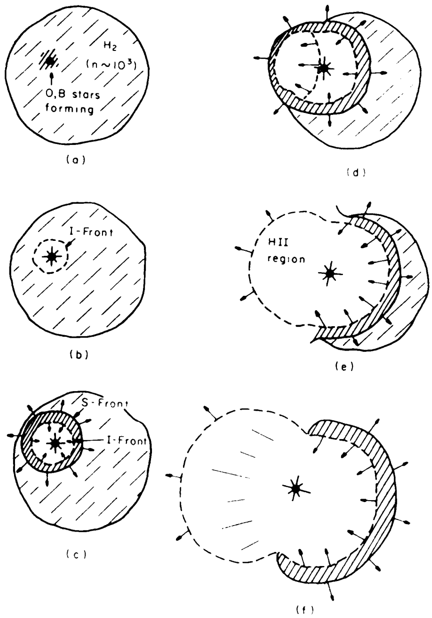

Fig. 2. Schematic diagram of the evolution of an HII region -- molecular cloud complex.

The various cloud destruction mechanisms can be compared in a general way. Estimates of the star formation rate indicate that the conversion of gas into stars proceeds at a rate $\dot{M}$ = 1 to 5 $M_\odot$ yr^{-1} in the entire galaxy (Mezger 1978, Scoville and Herch 1979), corresponding to a mean rate of 2.5 - 12 x 10^2 $M_\odot$ in 10^6 yrs per cloud, assuming a galactic population of 4,000 clouds (Solomon, Sanders, and Scoville 1980). Dissociation, ionization, and dispersal are likely to occur only after an episode of OB star formation and the creation of an HII region in the cloud. The effects of supernovae and stellar winds are minor in comparison with the damage caused by the evolving HII region (Lada, Blitz, and Elmegreen 1978). The conversion of H_2 into HI is followed by ionization when the gas flows through the ionization front at the HII region boundary. The conversion rate $\dot{M}$ is controlled by the expansion of the HII region since the available flux of ionizing photons depends on the recombination rate in the ionized gas. From the equations governing the size of an HII region as a function of time, and the Strömgren condition (see Spitzer 1968), it follows that

$$\dot{M} = 1.09 \times 10^{-9} \frac{Q^{2/3}}{n_o^{1/3}} \left[1 + 1.98 \times 10^2 \frac{n_o^{2/3}}{Q^{1/3}} t\right]^{-1/7} \text{ (gm s}^{-1}\text{)}$$

Table 1: Parameters of W80 and the expanding molecular shell.

W80		Expanding Shell	
distance	1 kpc	expansion velocity	5 km s^{-1}
ionizing flux	$5x10^{49}$ s^{-1}	mass of shell	$3\text{-}6x10^{4}$ $M_{\odot}$
HII mass	$1.8x10^{4}$ $M_{\odot}$	radius of shell	20 pc
diameter	50 pc	shell thickness	2-3 pc
electron density	9 cm^{-3}	expansion center	$\alpha = 20^{h}53^{m}15^{s}$
			$\delta = 43°45°00^{s}$

where equality holds for a Strömgren sphere. For an HII region that has burst out of the molecular cloud and is density bounded on one side $\dot{M}$ can be 2 or 3 times greater since removal of ionized gas from the region between the star and the molecular cloud increases the flux of photons available at the I-front. For an 05 star (Q = 5 x 10^{49} photons s^{-1}) and a cloud of uniform density n_0 = 500 cm^{-3}, $\dot{M} \gtrsim 2x10^{-3}$ $M_{\odot}$ yr^{-1}, close to the rate required to generate the W80 HII region if allowance is made for the removal of ionized gas.

A very crude estimate of the conversion rate of H_2 into HII on a galactic scale can be made on the basis of the total ionization rate in the galaxy (Smith et al. 1978, Mezger 1978). Assuming that the flux of Lyman continuum photons responsible for ionization of all galactic radio HII regions is Q = 4.7 x 10^{52} s^{-1} (corresponding to 16% of all OB stars in the galaxy), the conversion rate for the galaxy is $\dot{M}_g \gtrsim 2$ $M_{\odot}$ yr^{-1}, comparable to the mean star formation rate. The mean rate at which gas is accelerated to escape velocity from clouds by the rocket effect is difficult to estimate, in general. In the case of W80, the mass of the expanding shell is comparable to the mass of the ionized gas, implying that the mean disruption rate is similar to the ionization rate. Assuming that star formation continues at a steady rate in each cloud, disruption and ionization appear to be the dominant modes of cloud destruction once OB star formation has occurred. More detailed studies of the evolved complexes associated with S155, S184, S125 and other regions are continuing at the FCRAO in order to quantify the relative importance of various cloud destruction mechanisms.

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DISCUSSION FOLLOWING BALLY

de Jong: The H_2 shells that you discussed would put a lot of kinetic energy into the interstellar medium. Have you compared this energy input with, for instance, the energy input from supernova explosions?

Bally: Yes. The energy input is quite comparable to that from a supernova if the input due to dissociated gas is included. It is difficult to estimate on a galactic scale the ratio of gas surviving as H_2, to gas that has been dissociated.

Slysh: There is a supernova remnant in the region you mapped. It was in the list presented in my talk.

Bally: The SNR G84.2-0.8, to which you refer, is at a distance of roughly 17 kpc, as determined from the Σ-D relation. It is a background source not related to the W80 complex.

Mouschovias: While a cloud of density $\gtrsim 10^4 \mathrm{cm}^{-3}$ is waiting to be churned by an HII region, why is it not collapsing within the free-fall time of about 10^5 yrs? Large linewidths do not necessarily imply support by some unknown mechanism against collapse if they are due to ordered motions.

Bally: Observations show that clouds are *not* forming stars at the rate indicated by the free-fall time scale, so there must be some form of internal support. Turbulence and many forms of ordered motion would damp out too quickly, and there is *no* evidence for all-pervasive *small scale* ordered motion. Some source of pressure, added to the thermal pressure, could support the clouds *and* explain the large observed line widths. For instance, magnetic fields can, in some situations, raise the effective sound speed and act as this source of pressure.

Mouschovias: A word of caution on the rocket effect: since a cloud is not a rocket (i.e. not a solid), a fluid element at one point will not be affected by an expanding HII region until the shock front arrives. Since the length scales that concern you are typically $\gtrsim 20$ pc, and shock velocities are ~ 1 km s^{-1}, a cloud will be affected only in a time $\gtrsim 10^7$ yrs. Is this time-scale compatible with the ideas of churning and dispersing clouds over a few million years?

Bally: Although the shock velocity in our models can reach values as low as 1 km s^{-1}, it is generally larger over most of the lifetime of the region. The numerical models of the W80 region indicate that the *mean* shock velocity is about 5 km s^{-1} between the time of formation of the weak D front and the present. The rocket effect raises the shock velocity above the value it would have for a Strömgren sphere of equivalent radius. The reason is that the post-shock layer stops accumulating matter once it passes the position of the initial cloud boundary and enters the rocket phase.

Mouschovias: Would a dense, massive cloud be dispersed if self-gravity is taken into account (see 1976, Ap. J., 207, 141)?

Bally: Except in the case of *extremely* dense molecular clouds, gravity is not capable of halting the expansion of an HII region and the dispersal of the gas accelerated in the post-shock layer.