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OBSERVATIONAL EVIDENCE FOR TRIGGERED STAR FORMATION ON SCALES OF 1 TO 300 PC

S. T. Megeath,[1] B. Biller ,[1] T. M. Dame,[1] E. Leass,[1,2] R. S. Whitaker,[1,3] and T. L. Wilson[4]

RESUMEN

Presentamos evidencia para la formación estelar estimulada a dos escalas espaciales distintas en el complejo de nubes moleculares NGC 281. Este complejo notable se ubica 300 pc arriba del plano galáctico y parece pertenecer a un anillo de nubes atómicas y moleculares con diámetro de 270 pc que se está expandiendo a 22 km s^{-1}. Sugerimos que el anillo se formó en la expansión de una superburbuja impulsada por estrellas OB en el plano de la galaxia. Dentro del complejo de nubes, los datos combinados en las longitudes de onda ópticas, infrarrojas cercanas, milimétricas y centimétricas detallando la interacción entre una estrella O joven y los núcleos moleculares vecinos proporcionan evidencia de formación estelar estimulada dentro del complejo de nubes a una escala de unos pocos parsecs. Estos datos sugieren que están operando dos modos de formación estelar estimulada en el complejo NGC 281—primero la formación del complejo entero fue estimulada por supernovas y, después de la formación de la primera generación de estrellas O, la estimulación subsecuente de la formación estelar fue ocasionada por la compresión de la nube molecular empujada por la fotoevaporación.

ABSTRACT

We present evidence for triggered star formation on two different spatial scales in the NGC 281 molecular cloud complex. This remarkable complex is situated 300 pc above the Galactic plane, and appears to be part of a 270 pc diameter ring of atomic and molecular clouds expanding at 22 km s^{-1}. We suggest that the ring has formed in a superbubble blowout driven by OB stars in the plane of the Galaxy. Within the cloud complex, combined optical, NIR, mm and cm data detailing the interaction of a young O star with neighboring molecular cores, provide evidence of triggered star formation inside the cloud complex on a few parsec scale. These data suggest that two modes of triggered star formation are operating in the NGC 281 complex—the initial supernovae triggered formation of the entire complex and, after the first generation of O stars formed, the subsequent triggering of star formation by photoevaporation-driven molecular core compression.

Key Words: **H II REGIONS — ISM: CLOUDS — ISM: BUBBLES — STARS: FORMATION**

1. INTRODUCTION AND RESULTS

The NGC 281 nebula is an H II region situated in the Perseus arm of the Galaxy at a distance of 2.9 kpc. Elmegreen & Lada (1978) first proposed that the expansion of the H II region is triggering star formation in an adjoining molecular cloud. Multiwavelength observation of the clumpy molecular cloud/H II region interface provides further evidence of triggered star formation, although through a different mechanism than that originally proposed by Elmegreen & Lada. The evidence is summarized in Figure 1, which displays the most active star-formation site in NGC 281 (also see Megeath & Wilson 1997). Three panels display the spatial $C^{18}O$ contours: these contours show two dense ($n_{H_2} \sim 10^4$ cm^{-3}) molecular cores, which compose a ridge of molecular gas at the edge of the optical H II region. The VLA 20 cm data (lower left panel) show a parallel ridge of ionized gas. With the exciting O star of the H II region four parsecs to the northeast of the cores (outside the displayed field), the 20 cm emission appears to be tracing ionized gas photoevaporated off the surfaces of the clumps. At the current rate of photoevaporation, the cores can persist for 2.5 Myr. Interestingly, our recent *Hubble Space Telescope* (*HST*) WFPC2 images of the Hα emission at the interface (upper right panel) do not detect any small (1000 AU) diameter globules (or EGGs) similar to those found in *HST* images of the photoevaporating columns in M 16 (Hester et al. 1996). Finally, the near-IR image (upper left panel) shows a dense cluster of stars concentrated in the northern halves of the cores and in the adjoining H II region. In contrast, the southern halves of the cores are relatively devoid of stars. At the very southern edge of the field we see stars associated with a second distinct sub-cluster in NGC 281 (Megeath & Wilson 1997).

The estimated pressure of the ionized gas at the clump surfaces is twice the turbulent pressure of the molecular cores (Megeath & Wilson 1997), suggest-

[1]Harvard Smithsonian Center for Astrophysics, USA.
[2]University of Texas at Austin, USA.
[3]Swarthmore College, USA.
[4]Max Planck Institut für Radioastronomie, Germany.

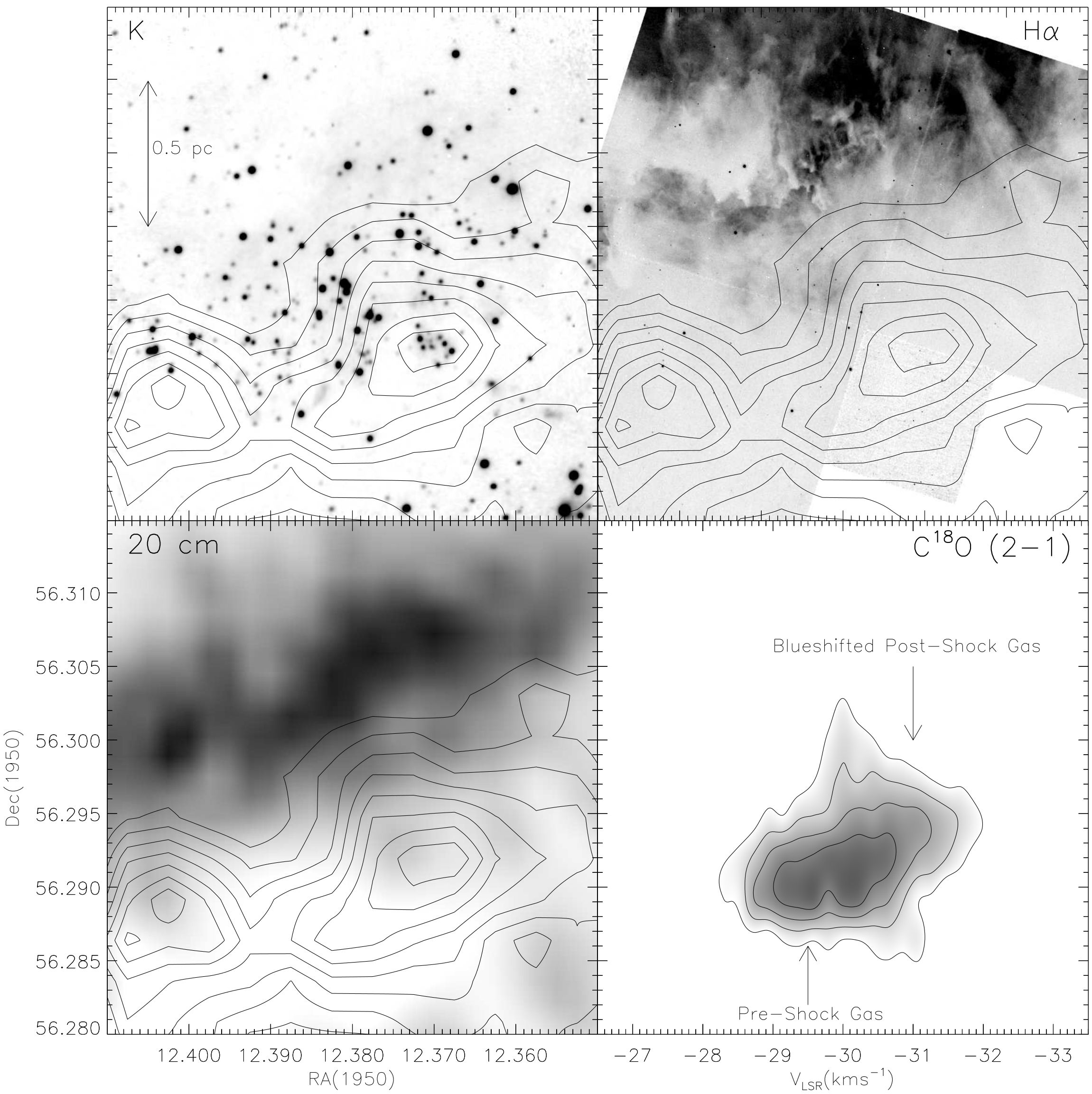

Fig. 1. Star formation in the NGC 281 H II/molecular interface shown at four different wavelengths.

ing that the photoevaporation is driving shocks into the molecular cores. Further evidence for shocks is found in a velocity shift apparent in the Declination vs. $V_{\rm LSR}$ diagram of the western core (lower right panel). These data suggest that the observed cores formed within the molecular cloud, and were exposed to the direct UV radiation when the lower density gas was swept away. The resulting sudden increase in pressure resulted in shockwaves. The propagating shocks then triggered the formation of stars, which first appear in the compressed post-shock gas and then emerge into the H II region, leading to the observed distribution of stars.

A remarkable property of the NGC 281 nebula is its location 300 pc from the Galactic plane. Large scale ^{12}CO maps and H I maps of the Perseus arm of the Galaxy (top panel of Figure 2; ^{12}CO data from Dame, Hartmann, & Thaddeus 2001; H I data from Hartmann & Burton 1997) show that the NGC 281 Nebula ($l = 123°$, $b = -6°$) is associated with a complex of relatively high-latitude molecular (contours) and atomic (grayscale) clouds as outlined by the rectangle in the top panel of Fig. 2. The l vs. $V_{\rm LSR}$ diagram (lower left panel) shows that the atomic and molecular clouds form a broken ring (note: at velocities $< 20\,{\rm km\,s^{-1}}$ the local H I dominates), indicative of a ring of clouds expanding at $22\,{\rm km\,s^{-1}}$. The resulting dynamical age is 6 Myr. The b vs. $V_{\rm LSR}$ diagram (lower right panel—the complex is outlined by a rectangle) shows that the ring extends down to

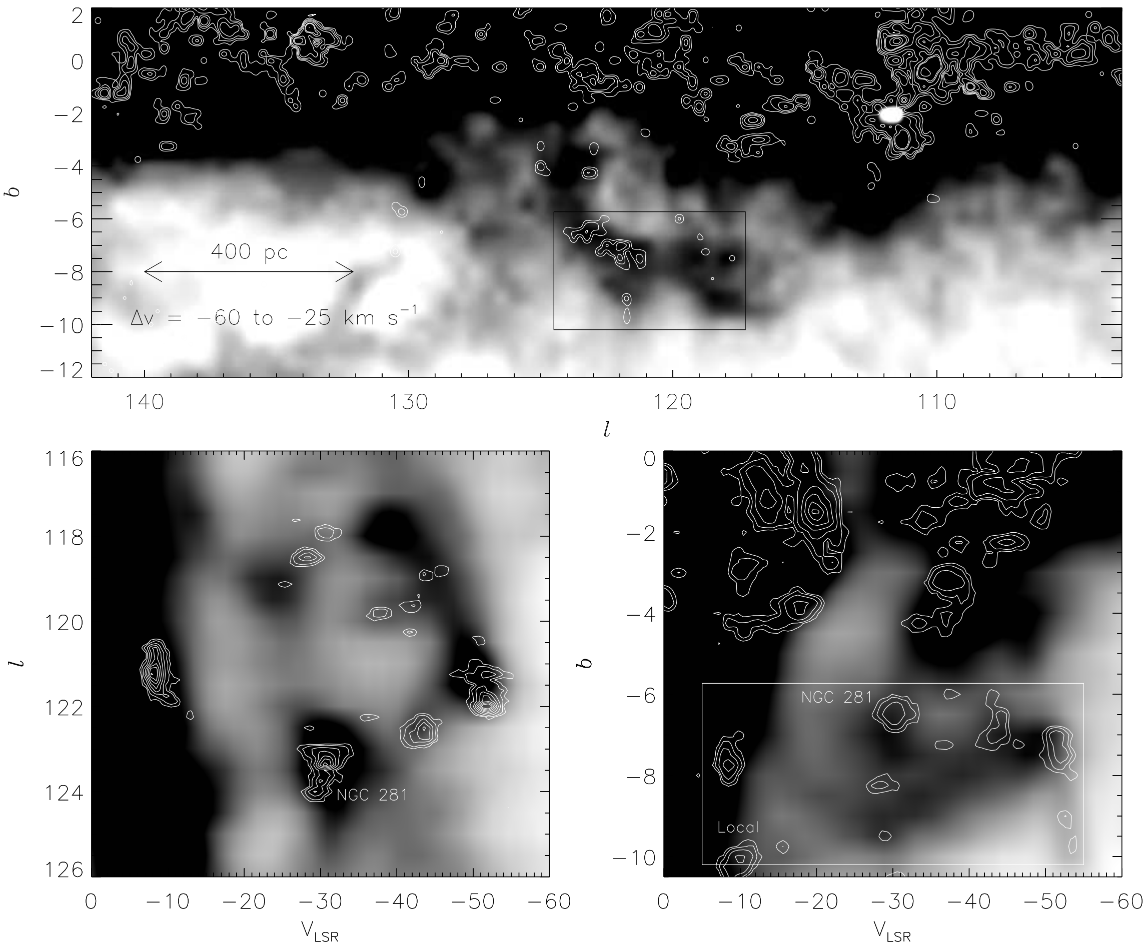

Fig. 2. The large-scale morphology and kinematics of the atomic and neutral gas from three perspectives.

$b = -10°$, even at a $V_{\rm LSR}$ of $53\,{\rm km\,s^{-1}}$! The total kinetic energy of the ring is 4.5×10^{51} erg, requiring the energy of multiple supernovae.

Both the high Galactic latitude and large expansion velocity may be explained if the NGC 281 complex originated in the blowout of an expanding superbubble. The loop of H I seen extending from the Galactic plane (upper panel) may trace the edge of a superbubble powered by supernovae near the Galactic plane. The expansion of a superbubble into the increasingly rarefied Galactic atmosphere can lead to a runaway expansion of the shell and the blowout of the bubble into the Galactic atmosphere. Numerical simulations show that blowouts produce fragments with velocities tangential to the Galactic plane as high as $50\,{\rm km\,s^{-1}}$ (Mac Low, McCray, & Norman 1989), suggesting that the molecular clouds of NGC 281 could have formed in the gas swept up and compressed in a blowout. Hence, NGC 281 may be an example of the supernovae-driven formation of molecular clouds (and consequently, supernovae-triggered star formation) on a scale of 300 pc.

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B. Biller, T. M. Dame, E. Leass, S. T. Megeath, and R. S. Whitaker: Harvard Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA, USA (tdame,tmegeath@cfa.harvard.edu).
T. L. Wilson: Max Planck Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany (p073twi@mpifr-bonn.mpg.de).