A LUMINOUS BLUE VARIABLE STAR INTERACTING WITH A NEARBY INFRARED DARK CLOUD

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ABSTRACT

G79.29+0.46 is a nebula created by a luminous blue variable (LBV) star candidate characterized by two almost circular concentric shells. In order to investigate whether the shells are interacting with the infrared dark cloud (IRDC) G79.3+0.3 located at the southwestern border of the inner shell, we conducted Jansky Very Large Array observations of NH3(1, 1), (2, 2) and C2H, and combined them with previous Effelsberg data. The overall NH3 emission consists of one main clump, named G79A, elongated following the shape of the IRDC, plus two fainter and smaller cores to the north, which spatially match the inner infrared shell. We analyzed the NH3 spectra at each position with detected emission and inferred linewidth, rotational temperature, column density, and abundance maps, and find that: (1) the linewidth of NH3(1, 1) in the northern cores is 0.5 km s⁻¹, slightly larger than in their surroundings; (2) the NH3 abundance is enhanced by almost one order of magnitude toward the northwestern side of G79A; (3) there is one “hot slab” at the interface between the inner infrared shell and the NH3 peak of G79A; and (4) the western and southern edges of G79A present chemical differentiation, with C2H2 tracing more external layers than NH3, similar to what is found in photon-dominated regions. Overall, the kinematics and physical conditions of G79A are consistent with both shock-induced and UV radiation-induced chemistry driven by the LBV star. Therefore, the IRDC is not likely associated with the star-forming region DR15, but located farther away, near G79.29+0.46 at 1.4 kpc.

Key words: ISM: individual objects (G79.29+0.46, G79.3+0.3) – ISM: lines and bands – radio continuum: ISM – stars: formation

Online-only material: color figures

1. INTRODUCTION

Luminous blue variable (LBV) stars are massive stars undergoing ejection events before their explosion as a Type II supernova (e.g., Groh et al. 2013; Vamvatira-Nakou et al. 2013). Although understanding massive star evolution is crucial in our understanding of galactic-scale phenomena, the details of the mass-loss episodes during the LBV phase are not well known yet. This is because to properly model these ejection events, it is required a basic knowledge of the properties of the interstellar medium surrounding the LBV star. However, only a few LBV stars have been studied in detail together with their surrounding medium (e.g., Rizzo et al. 2001; Loinard et al. 2012).

G79.29+0.46 is a nebula projected toward the center of the Cygnus OB2 association, ~10° to the northwest of the massive star-forming region DR15, and ~1’ to the north of the infrared dark cloud G79.3+0.3 (hereafter the IRDC; see Figure 1). The distance to G79.29+0.46 is adopted to be ~1.4 kpc (Rizzo et al. 2014, referred to as “Paper I”). G79.29+0.46 has two almost-circular concentric shells surrounding the star, with the inner one emitting from the mid-infrared (Jiménez-Esteban et al. 2010) up to the centimeter range (Higgs et al. 1994; Umana et al. 2011). In addition, G79.29+0.46 harbors the LBV candidate with one of the clearest and best studied shells of CO gas (e.g., Rizzo et al. 2008; Petriella et al. 2012; Paron et al. 2012), and is the only candidate with a molecular shell detected in NH3 (Paper I). Thus, G79.29+0.46 seems to have formed in a particularly dense cloud which was not fully disrupted soon after the birth of the LBV star. What is more, the southwestern side of the molecular shell shows hints of interaction with the surrounding medium.

Rizzo et al. (2008) report shocked CO in the southwestern side of the shell, at the position of the clump named G79A, where Umana et al. (2011) also suggest interaction between the shell and the surrounding dense gas, based on the morphology of the centimeter emission at that position. Very recently, in Paper I, we report an NH3 over-abundance toward the northern edge of G79A, and suggest that it could be produced by the passage of a low-velocity shock. Thus, G79A turns to be one of the best laboratories to study the direct interaction of LBV ejecta and the surrounding interstellar medium. In this Letter, we combine the Effelsberg observations presented in Paper I with new interferometric data in G79A, and provide a close-up view of the physical processes involved in such an interaction.

2. OBSERVATIONS

We used the Jansky VLA5 (JVLA) on 2010 July 21, and 2010 August 9 and 14 to observe the metastable lines (J, K) = (1, 1) and (2, 2) of NH3 (first and third days) and the JKa = 11,0–10,1 rotational transition of C2H2, under the project AP581, with the array in the D configuration. The projected baselines ranged from 40 to 1010 m. The phase center of the observations was (R.A., decl.)2000 = (20:31:37.90, +40:19:59.0), and the FWHM of the primary beam at the frequency of the observations is 2.2. NH3(J, 1) and (2, 2) were observed simultaneously in full polarization mode, with spectral windows of 1.0 MHz and a channel spacing of 15.625 kHz (0.20 km s⁻¹; rest

5 The Very Large Array (VLA) is operated by the National Radio Astronomy Observatory (NRAO), a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
frequencies 23694.495 and 23722.633 MHz). This allowed us to cover the main line and one inner satellite of the (1, 1) transition, and the main line of the (2, 2) transition. C3H2 was observed in dual polarization, with a spectral window of 2.0 MHz and a channel spacing of 7.813 kHz (0.13 km s\(^{-1}\)). We observed it in dual polarization, with a spectral window of 2.0 MHz and a channel spacing of 7.813 kHz (0.13 km s\(^{-1}\)). Rest frequency 18343.143 MHz. Data were calibrated using the software CASA (McMullin et al. 2007), following the standard calibration procedures. Passband response was obtained from observations of 3C84, and phase was calibrated using the same quasar J2015+3710, for which we measured bootstrapped phases of 3.26 ± 0.03 Jy, 3.29 ± 0.01 Jy, and 3.82 ± 0.03 Jy on the three observing days. The third day suffered from a flux calibration problem yielding an uncertainty in the absolute flux scale of 20%. Imaging and combination with Effelsberg data (from Paper I) was done using MIRIAD (Sault et al. 1995) for a taper of 10\(^{\prime\prime}\) and sampling the zero-spacing \(\mu v\)-hole with 500 visibility points generated with the single-dish data. The final rms of the combined NH3(1, 1) image is 9 mJy beam\(^{-1}\), and the synthesized beam is 14\(\prime\)63 × 10\(\prime\)57, with P.A. = 51\(^\circ\)16. For the NH3(2, 2) image the rms is 7 mJy beam\(^{-1}\), and the beam is 15\(\prime\)45 × 10\(\prime\)47, P.A. = 51\(^\circ\)56. For C3H2, the final JVLA-only cleaned images have a synthesized beam of 9\(\prime\)04 × 8\(\prime\)05, P.A. = 19\(^\circ\)76, and an rms per channel of 3 mJy beam\(^{-1}\).

3. METHODOLOGY

In order to infer the physical parameters from the NH3 (Effelsberg + JVLA) emission we extracted NH3(1, 1) and (2, 2) spectra in a regular grid of 4\(\prime\) × 4\(\prime\) covering all the NH3(1, 1) emission and fitted the hyperfine structure of the NH3(1, 1) emission for those spectra with signal-to-noise ratio (S/N) larger than 4, and fitted a Gaussian profile to the NH3(2, 2) line for those spectra with S/N larger than 3. All the spectra present emission at \(v_{\text{LSR}} \sim 1\) km s\(^{-1}\) (approximately ranging from 0.5 to 1.5 km s\(^{-1}\)), but some particular spectra show additional velocity components in the range \(-2.5\) to \(2.5\) km s\(^{-1}\). By following the same methodology described in detail in the Appendix of Busquet et al. (2009), we inferred the velocity, linewidth, opacity of the main line (ranging from \(\lesssim 1\) to 3), total column density (corrected for the primary beam response) and rotational temperature \(T_{\text{rot}}\) for each point of the grid, for the velocity component at 1 km s\(^{-1}\), and built maps for these parameters. Multiple velocity components in the spectra were fitted individually. The rotational temperature \(T_{\text{rot}}\) was estimated at those positions where both NH3(1, 1) and NH3(2, 2) were detected. Wherever NH3(2, 2) was not detected but NH3(1, 1) was, we calculated the upper limit of \(T_{\text{rot}}\) to be \(~12\) K. Since this upper limit is very close to the lowest \(T_{\text{rot}}\) typically seen in starless cores (~8–10 K), by adopting this upper limit for \(T_{\text{rot}}\) we provide reasonable NH3 column density and abundance estimates at the positions with only NH3(1, 1) detected. Typical uncertainties in the rotational temperature are around 1–2 K. Note also that \(T_{\text{rot}}\) inferred from NH3(1, 1) and (2, 2) lines is a good approximation to the kinetic temperature for \(T_{\text{rot}} \lesssim 25\) K (e.g., Walmsley & Ungerechts 1983; Danby et al. 1988).

Last, we built an NH3 abundance map by using our inferred NH3 column density and estimating the H2 column density from the Motte et al. (2007) 1.2 mm continuum image (after convolving the NH3(1, 1), (2, 2) channel maps, and the 1.2 mm image to the same beam of 15\(\prime\)\(\prime\)). To convert to H2 column density we assumed a dust temperature of 10 K, an opacity at 1.2 mm of 0.010 cm\(^2\) g\(^{-1}\) (Ossenkopf & Henning 1994), and a gas-to-dust ratio of 100 (see the Appendix of Paper I for further details).

4. RESULTS

The bulk of the NH3(1, 1) emission is found at \(v_{\text{LSR}} \sim 1\) km s\(^{-1}\), similar to the systemic velocity of the IRDC (Redman et al. 2003; Higuchi et al. 2013). However, an important number of positions, both in NH3(1, 1) and (2, 2), presents additional velocity components ranging from \(-2.5\) to \(2.5\) km s\(^{-1}\), consistent with the range where we discovered the NH3 counterpart of the LBV shell (Paper I). Figure 2 presents the distribution of the zero-order moment of the combined (Effelsberg + JVLA) NH3(1, 1) and (2, 2) data toward G79A. The NH3(1, 1) emission consists of one main centrally-peaked clump with some substructure being elongated in the (south)east–(north)west direction. The NH3 (1, 1) clump follows the large-scale elongation of the IRDC at the position (Figure 1), its peak falls about \(~30\)\(\prime\) to the south of the inner shell, and is coincident with a 70\(\mu m\) source and a secondary peak about \(~30\)\(\mu m\) closer to the north of the G79A core. Interestingly, the NH3(2, 2) integrated emission presents a secondary peak about \(~10\)\(\prime\) to the north of the G79A peak, exactly at the border of the LBV shell (and labeled as G79An; see below for further details).
In Figure 3 we present the maps of the linewidth, $T_{\text{rot}}$, column density, and NH$_3$ abundance for the velocity component at 1 km s$^{-1}$ (corresponding to the IRDC). The linewidth is around 0.3–0.4 km s$^{-1}$ in almost all the clump, except in two separated regions where it reaches values $>0.5$ km s$^{-1}$. One of the regions is mainly associated with the southeastern part of the G79A clump. The other coincides with the NE and N cores, at the shell location. The rotational temperature map reveals a region of enhancement toward the southwest of G79A, with $T_{\text{rot}}$ up to 13 K, which is almost devoid of mid/far-infrared sources, while $T_{\text{rot}}$ decreases down to 8 K toward the northwest and southeast of G79A. The temperature is $\sim$10 K around the G79A peak, where several infrared sources are located. The NH$_3$ column density reaches its highest value at the G79A peak, and extends along the southeast–northwest direction. As for the NH$_3$ abundances, we find values ranging from $1 \times 10^{-8}$ to $9 \times 10^{-8}$, and interestingly the NH$_3$ abundance peak is shifted with respect to the G79A peak about $\sim$40" toward the northwest, close to the position of the shock reported by Rizzo et al. (2008; star symbol in Figures 2 and 3).

As mentioned above, the NH$_3$(1, 1) and (2, 2) spectra show multiple velocity components ranging from $-2.5$ to $+2.5$ km s$^{-1}$. The velocity components (different to 1 km s$^{-1}$ of the IRDC) with higher intensity are found at 2.3 and $\sim-2$ km s$^{-1}$, and are detected only in the NH$_3$(2, 2) line. These velocity components are responsible for the secondary peak G79An (Figure 2, bottom). Figure 4 shows the NH$_3$(2, 2) channels at $-2.1$ and 2.3 km s$^{-1}$, overplotted on the 6 cm and 1.2 mm emission, and reveals that these velocity components arise from material located in between the G79A peak and the LBV shell. Since G79An is not detected in NH$_3$(1, 1), we infer a lower limit of $T_{\text{rot}}$ of 40 K, much warmer than the typical values measured for the 1 km s$^{-1}$ component of the IRDC (Figure 3). In addition, a two-dimensional Gaussian fit to G79An at 2.3 km s$^{-1}$ yields a size of $26'' \times 14''$ with P.A. = $-68^\circ$, which matches the elongation of the shell at this position. These velocity components point to the presence of a “hot slab” at the interface of the LBV shell and G79A, which is not associated with 8 or 70 $\mu$m point-sources (Figure 4).

In Figure 5 we present the emission of c-C$_3$H$_2$ obtained using the JVLA data only (bottom panel) overplotted on a Spitzer 24 $\mu$m image (Jiménez-Esteban et al. 2010). For comparison, we plot the emission of NH$_3$(1, 1) using also JVLA data only (top panel). Thus, both data sets are filtering out the same large spatial scales. While the emission of NH$_3$(1, 1) is following mainly a “tilted-L” shape, with the northern arm following the inner shell at 24 $\mu$m, the c-C$_3$H$_2$ emission is present toward the western side of G79A where no NH$_3$ is found. To compare the c-C$_3$H$_2$ emission to the NH$_3$(1, 1) emission, in Figure 5 (bottom) we connect with black lines the peaks of c-C$_3$H$_2$, and overplot in red lines the connected peaks of NH$_3$(1, 1). The figure shows that the black lines tracing c-C$_3$H$_2$ are located farther to the south and to the west as compared to the red lines tracing NH$_3$, and thus c-C$_3$H$_2$ seems to trace material from outer layers of the G79A clump.

Finally, we calculated some physical parameters of G79A from the millimeter continuum emission. Using the 1.2 mm data of Motte et al. (2007), we estimated a mass for G79A of 80–150 $M_\odot$, for dust temperatures from 10 to 15 K, and adopting the same opacity and dust-to-gas ratio given in Section 3, and the same distance as the LBV star (1.4 kpc; see Section 5). The uncertainty in the masses due to the opacity law is estimated to be a factor of two. For the size, a two-dimensional Gaussian fit to the 1.2 mm continuum clump yields a deconvolved size of 44" in diameter. This corresponds to a density in G79A of $8.4 \times 10^5$ cm$^{-3}$.

5. DISCUSSION AND CONCLUSIONS

The NH$_3$(1, 1) and (2, 2) and c-C$_3$H$_2$ data presented in this work reveal a number of features which definitely confirm an interaction of the infrared shells created by the LBV star with the IRDC. This has been possible because of the combination of both JVLA and Effelsberg data, allowing us to recover information from large ($\sim 1$ pc) to small ($\sim 0.05$ pc) spatial scales.

First, we find an increase of the NH$_3$ abundance toward the northwest of G79A, of one order of magnitude (up to $9 \times 10^{-8}$). In Paper I, we report also an abundance increase to the north of G79A, but could not accurately determine its position because
we used Effelsberg data alone. In this Letter we find that the NH₃ increase takes place precisely at the position where Rizzo et al. (2008) report a shock in CO (3–2). Overall, this suggests that the northwestern part of the G79A clump is being shocked by the expanding shell of the LBV star, releasing NH₃ molecules from the dust grains back to the gas phase. Viti et al. (2011) model the effects of the propagation of a C-type shock into dense (∼10⁵ cm⁻³) interstellar material, including the sputtering of dust grains, and predict an increase in NH₃ abundance from 10⁻⁹ up to ∼10⁻⁶, depending on the particular conditions of the shock and pre-shock material. This NH₃ abundance increase is consistent with our observations, and the physical conditions adopted in the model are also consistent with those in G79A, as the density in G79A is estimated to be ∼10⁵ cm⁻³ (Section 4), and the velocity required for efficient sputtering of dust grains is ≥10 km s⁻¹ (van Loo et al. 2013), similar to the shock velocity measured by Rizzo et al. (2008). An increase of NH₃ abundance in cores shocked by the passage of an outflow is also observed in star-forming regions, such as HH 2 (Torrelles et al. 1992; Girart et al. 2005).

Further evidence of the gas in G79A being shocked comes from the “hot slab” found near the G79A peak (Figure 4). The different velocity components and T_{rot} of this “hot slab” are fully consistent with the Effelsberg spectrum of NH₃(3, 3) near the same position (Paper I). Thus, the high angular resolution data reported in this work allowed us to locate the origin of the NH₃(3, 3) hot velocity components discovered with single-dish. The facts that no mid/far-infrared point-sources are associated with the “hot slab,” that it is located at the interface between the LBV shell and the G79A peak, that it is elongated along the shell direction, and that their velocities are slightly different to that of the IRDC, all indicate that this “hot slab” is probably produced by shocks generated by the expanding shell from the LBV star.

Furthermore, our study suggests that the interaction of the LBV shell with the G79A clump is not only through shocks, but also radiative. This is suggested by a temperature enhancement (up to 12–13 K) extending ∼40″ in the southwestern part of the G79A clump, which is almost devoid of mid/far-infrared sources and thus could be produced by external heating. Moreover, in this southwestern region of G79A, c-C₃H₂ seems to trace the outer layers of the clump as compared to NH₃ (Figure 5). As expected in photon-dominated regions (PDRs), NH₃ is photo-destroyed in the outer parts of the PDR, while...
c-C$_3$H$_2$ is known to survive in hot regions ($\sim$100 K) for several $10^7$ yr (Hassel et al. 2011; Aikawa et al. 2012), as shown also by recent observations of the HorseHead nebula and Mon R2 PDRs (Rizzo et al. 2005; Gerin et al. 2009; Pilleri et al. 2013). The strong 24 $\mu$m emission surrounding not only the northern side of G79A but also the western and southern edges (Figure 5) is consistent with this scenario. Interestingly, the outer infrared shell lies exactly to the south of G79A (Gvaramadze et al. 2010; Jiménez-Esteban et al. 2010; Umana et al. 2011), and the IRDC is interrupted exactly to the west of G79A (Figure 5; Paper I), where the circular geometry of the inner shell is distorted (Umana et al. 2011). Thus, the southern and western edges of the G79A clump seem to be bathed by (mid-infrared) radiation probably coming also from the LBV star.

The characterization of the dense gas surrounding the G79.29+0.46 nebula, as well as the presented details of the interaction of the nebula with the IRDC, constitute an excellent base for future modeling of the mass-loss episodes of the underlying LBV star. In addition, in Paper I we show that the IRDC is probably located in between the DR15 massive-star forming region and the LBV nebula G79.29+0.46. The results presented in this work show for the first time clear evidence that the LBV ejecta and the IRDC are interacting. Thus, the IRDC G79.3+0.3 is not likely associated with the DR15 star-forming region at 800 pc, as usually assumed in the literature, but close to G79.29+0.46 at $\sim$1.4 kpc.

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