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# SHOCKED AMMONIA IN THE WOLF-RAYET NEBULA NGC 2359

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## ABSTRACT

We report the detection of the (1, 1) and (2, 2) metastable lines of ammonia ($NH_3$) in the molecular cloud associated with the Wolf-Rayet (W-R) nebula NGC 2359. Besides the CO and $H_2$, this is the first molecule detected in the environs of a W-R star. Width ($\Delta V_{1/2} = 3$ km s$^{-1}$) and radial velocity ($V_{LSR} \sim 54$ km s$^{-1}$) indicate that the $NH_3$ lines arise from the molecular cloud that is interacting with the W-R star. The rotational temperature derived from the (1, 1) and (2, 2) line intensity ratios is about 30 K, significantly larger than the typical kinetic temperature of the ambient gas of ∼10 K. The derived $NH_3$ abundance is $\sim 10^{-8}$. Line width, abundance, and kinetic temperature can be explained if $NH_3$ is released from dust grain mantles to the gas phase by shocks produced by the expansion of the bubble created by the W-R stellar wind. We briefly discuss the implications of the detection of warm $NH_3$ associated with a W-R star in connection to the hot $NH_3$ emission detected in the Galactic center and in the nuclei of external galaxies.

*Subject headings:* ISM: abundances — ISM: individual (NGC 2359) — ISM: molecules — stars: individual (HD 56925) — stars: Wolf-Rayet

## 1. INTRODUCTION

The interstellar medium surrounding Wolf-Rayet (W-R) stars is expected to be strongly disturbed by the fast stellar evolution with rapidly varying mass-loss rates, luminosities, and elemental composition of the ejecta. The W-R star HD 56925—WR 7 in the catalog of van der Hucht (2001)—excites the windblown bubble NGC 2359 (Chu, Treffers, & Kwitter 1983). The chemical enrichment (Esteban et al. 1990), the nearly spherical morphology, and the kinematics of NGC 2359 suggest a relatively recent origin for this nebula, probably produced in the W-R stage of the exciting star. The H II region that surrounds the windblown bubble seems to be confined by molecular material in the southern direction (Schneps et al. 1981). The spatial distribution of the 1–0 (1) line of $H_2$ (St-Louis et al. 1998) suggests that the $H_2$ vibrationally excited emission is produced by the interaction of the W-R star with the molecular material.

Recently, Rizzo, Martín-Pintado, & Mangum (2001, hereafter Paper I) have mapped the CO $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$, and the $^{13}$CO $J = 1 \rightarrow 0$ emission over the whole nebula. They found that the two velocity components toward the southern part of the nebula have LSR radial velocities ($V_{LSR}$) of 54 and 67 km s$^{-1}$. The 67 km s$^{-1}$ component has a narrow line width (1 km s$^{-1}$), indicating that this component traces quiescent material. On the other hand, the component with $V_{LSR}$ of 54 km s$^{-1}$ is broad (5 km s$^{-1}$), surrounds the southern and eastern parts of NGC 2359 (see Fig. 1*a*), and is spatially anticorrelated with the narrow component. The broad line widths and the spatial distribution of the 54 km s$^{-1}$ component indicate that it is affected by the interaction of the W-R star with the ambient material at 67 km s$^{-1}$. The shocks produced by the expansion of the stellar wind bubble are likely the origin of the line broadening.

Molecular chemistry can be an important tool to firmly establish if the molecular material in the broad component is affected by the strong shocks produced by the stellar wind from HD 56925. In particular, the ammonia ($NH_3$) fractional abundance changes from $10^{-10}$ in photodissociation regions to $10^{-6}$ in shocked regions. This is due to the fact that the $NH_3$ is a very fragile molecule, easily photodissociated by UV radiation (van Dishoeck 1988; Roberge et al. 1991), but it can also be released from icy grain mantles by shocks with moderate velocities (Flower & Pineau des Forêts 1994). In this Letter, we report the first detection of ammonia emission toward a W-R nebula. The rather high abundance of $NH_3$ and the kinetic temperature found in the broad velocity component is in agreement with the idea that the molecular gas has been shocked by the stellar wind from the W-R star HD 56925.

## 2. OBSERVATIONS AND RESULTS

The (1, 1) and (2, 2) metastable ammonia lines were observed using the Effelsberg 100 m radio telescope of the MPIR in 2000 December and 2001 March. The half-power beamwidth of the telescope at the rest frequency of the $NH_3$ lines, 23.7 GHz, was 40″. We used the new cooled dual-channel high electron mobility transistor *K*-band receiver with a typical system temperature of 230 K on a main-beam brightness temperature scale. An 8192-channel autocorrelator was used as the back end. Both ammonia lines were observed simultaneously with a total bandwidth of 20 MHz and a velocity resolution of 0.06 km s$^{-1}$. In order to improve the signal-to-noise ratio, the spectra were later smoothed to a resolution of 0.5 km s$^{-1}$. The observations were made in a dual beam–switching mode (switching frequency 1 Hz) with a beam throw of 121″ in azimuth. Pointing was regularly checked, and it was found to be within 5″. The data were calibrated using the continuum emission of NGC 7027 as the principal calibrator, assuming a flux density of 5.4 Jy at 23.9 GHz (Ott et al. 1994). Orion KL (Hermsen et al. 1988) was used as a line calibrator. Both calibrations agree to within 10%, and we conclude that line intensities on a main-beam temperature scale are accurate to within ±15%.

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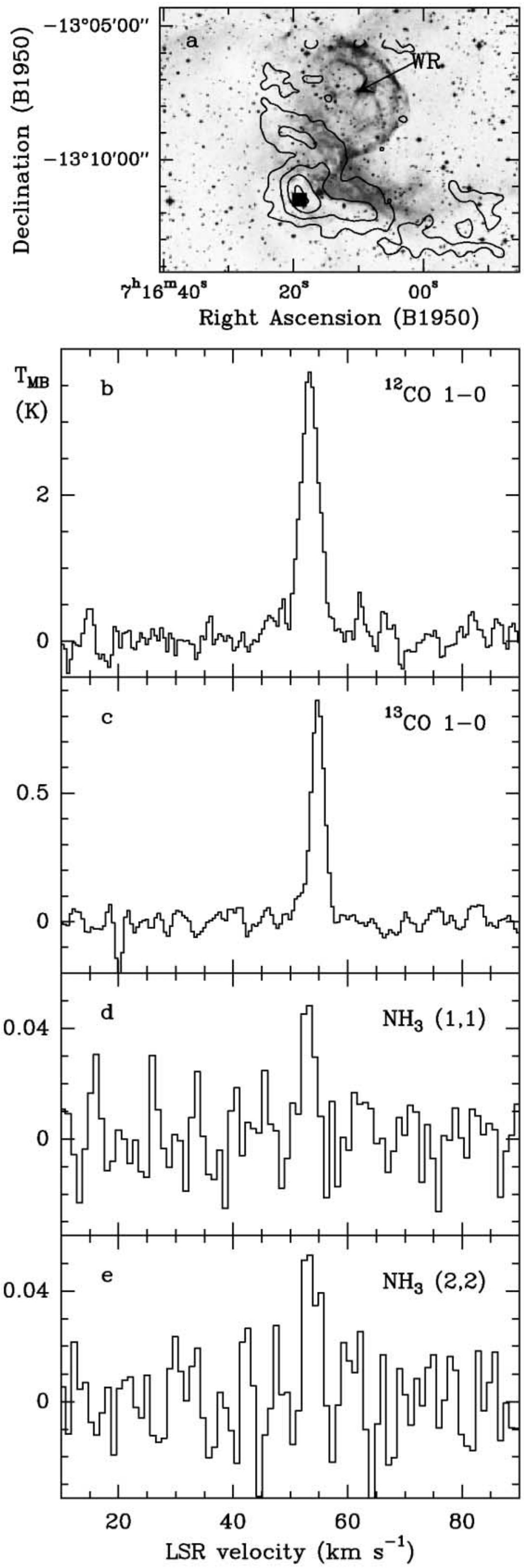


FIG. 1.—The $^{12}CO$, $^{13}CO$, and $NH_3$ emission toward the W-R nebula NGC 2359. The intensity distribution map in (*a*) corresponds to the CO $J = 2 \rightarrow 1$ emission (see Paper I). The individual profiles are from the filled square plotted onto the clump to the southeast of the optical nebula. The position of the WN4 star HD 56925 is indicated by an arrow. In the profiles from (*b*) to (*e*), the molecular transition is indicated at the top right corner.

TABLE 1

OBSERVATIONAL AND PHYSICAL PARAMETERS

| Parameter | Value |
|---|---|
| R. A., decl. (B1950) …… | $07^h16^m19^s$, $-13°11'26''$ |
| $NH_3$ (1, 1) fit: | |
| Peak temperature ……. | $53 \pm 6$ mK |
| LSR velocity ……….. | $53.1 \pm 0.6$ km $s^{-1}$ |
| Width profile ………. | $2.6 \pm 0.6$ km $s^{-1}$ |
| $NH_3$ (2, 2) fit: | |
| Peak temperature ……. | $46 \pm 7$ mK |
| LSR velocity ……….. | $53.6 \pm 0.6$ km $s^{-1}$ |
| Width profile ………. | $3.0 \pm 0.7$ km $s^{-1}$ |
| $N$(CO) ………………… | $\sim 7.0 \times 10^{16}$ $cm^{-2}$ |
| $N(NH_3)$ ………………. | $\sim 6.8 \times 10^{12}$ $cm^{-2}$ |
| $X(NH_3)$ ………………. | $\sim 1.0 \times 10^{-8}$ |
| $T_{rot}$ …………………… | $\sim$30 K |

Figure 1*a* shows the spatial distribution of the $^{12}CO$ $J = 2 \rightarrow 1$ emission of the broad component at $V_{LSR} = 53$ km $s^{-1}$ in NGC 2359, overlaid on an optical image of the W-R nebula. The filled square indicates the location of the maximum CO emission, which is also the position where the $NH_3$ data were taken. Figures 1*b*–1*e* show the line profiles of the $J = 1 \rightarrow 0$ lines of $^{12}CO$ and $^{13}CO$, and the (1, 1) and (2, 2) lines of $NH_3$, respectively. All the lines were measured with similar beam sizes of 40″–50″. Both ammonia lines are weak but clearly detected at 7–8 $\sigma$ levels. The observational parameters of the lines have been derived from Gaussian fits to the profiles of the (1, 1) and (2, 2) lines, and the results are shown in Table 1. The radial velocities and line widths are in good agreement with those of the broad CO component at 53–54 km $s^{-1}$, indicating that both CO and $NH_3$ emission arises from the same region.

Assuming optically thin emission for both ammonia lines, we have derived the (1, 1) and (2, 2) column densities given in Table 1. From the ratio of the (1, 1) and (2, 2) column densities, we estimate a rotational temperature of 30 K. Under typical conditions of the molecular gas, this rotational temperature can be considered as a lower limit to the kinetic temperature of the gas (Walmsley & Ungerechts 1983). Using a kinetic temperature of 30 K and considering only the five lowest metastable ($J = K$) levels for the partition function, we derive a lower limit to the total ammonia column density of $7 \times 10^{12}$ $cm^{-2}$. For a CO column density of $0.7 \times 10^{17}$ $cm^{-2}$ (Paper I) and assuming a fractional CO abundance of $10^{-4}$, we derive a $NH_3$ abundance of $(1 \pm 0.4) \times 10^{-8}$. This $NH_3$ abundance is comparable to those measured in cold galactic molecular clouds (Benson & Myers 1983) and shocked regions (Martín-Pintado & Cernicharo 1987; Tafalla & Bachiller 1995) but significantly higher than in photodissociation regions (Fuente et al. 1990).

## 3. DISCUSSION

The broad widths and the radial velocities of the (1, 1) and (2, 2) $NH_3$ lines indicate that the $NH_3$ emission arises from the gas that is interacting with the W-R nebula. Two different kinds of interaction between an evolved massive star and the surrounding material are expected: UV photodissociation and shocks produced by the stellar wind. It is well known that the UV radiation from hot stars dissociates fragile molecules, such as $NH_3$, even up to visual extinctions of 5 mag (i.e., $H_2$ column densities of $5 \times 10^{21}$ $cm^{-2}$). In this case, the photodissociation rate would be on the order of $10^{-7}$ $s^{-1}$ (van Dishoeck 1988). Hence, the relatively high $NH_3$ abundance is striking in view of the rather low $H_2$ column density of $\sim 10^{21}$ $cm^{-2}$ derived from the CO data. If the total extinction between the star and the $NH_3$ region would be comparable to the total extinction derived from the CO data, the $NH_3$ must be produced very efficiently in order to compete with its photodissociation due to the W-R star radiation field. From the dust continuum emission measured by the *IRAS* HiRes data at 60 and 100 $\mu$m (Aumann, Fowler, & Melnyk 1990; J. R. Rizzo et al. 2001, in preparation), we have derived a dust temperature of 29 K and a column density in the range (2–5) $\times$ $10^{16}$ $cm^{-2}$ toward the position where $NH_3$ is detected. These values were obtained from the color-corrected 60 and 100 $\mu$m emission maps smoothed to an angular resolution of 2′ and assuming an emissivity proportional to $\lambda^{-2}$. The dust grains were assumed to be spherical, of size 0.1 $\mu$m, and with a density of 3 g $cm^{-3}$ (Hildebrand 1983). Assuming the standard gas-to-dust ratio of 100, the total gas column density associated to the warm dust at 29 K is only $10^{18}$ $cm^{-2}$, at least 2 orders of magnitude below the total gas column density derived from CO in Paper I. This suggests that basically all the dust associated with the molecular gas cannot have temperatures of $\geq$10 K. The warm-dust component measured by *IRAS* is likely associated to the material affected by the UV radiation from the W-R star, shielding the warm gas from dissociation. The gas in the broad component seems to be warmer than the dust.

The presence of shock fronts acting in this region could explain both the $NH_3$ abundance and the gas kinetic temperature higher than the dust temperature in the broad component. A C-shock of 10–15 km $s^{-1}$ would heat the gas up to the temperatures derived from our data and release the $NH_3$ from the dust grain icy mantles (Flower & Pineau des Forêts 1994) to achieve the observed abundance. García-Segura & Mac Low (1995a, 1995b) have modeled the dynamical evolution of W-R bubbles and predicted the presence of several shock fronts running into the surrounding gas at the different stages of the evolution of massive stars. When the W-R stellar wind shocks the previous red supergiant ejecta, an expansion velocity of ~10–15 km $s^{-1}$ is expected for the shocked gas. This velocity is in good agreement with the velocity separation of 12–13 km $s^{-1}$ measured between the shocked and the quiescent gas (Paper I).

The Galactic center (GC) region is known to contain large amounts of warm gas with relatively high abundance of molecules like $NH_3$, SiO, and $C_2H_5OH$ extended over relatively large regions (Hüttemeister et al. 1995; Martín-Pintado et al. 1997, 2001). This warm gas seems to be associated with the cold dust, and a shock chemistry has been claimed to explain the heating, the abundances, and the densities of these molecules in the GC. However, the origin of the widespread shocks is, so far, unknown. Martín-Pintado et al. (1999) have recently found that a large fraction of the hot $NH_3$ in the Sgr B2 envelope is located in shells of 1–2 pc, expanding at 8–10 km $s^{-1}$. The large $NH_3$ abundance and the rather high kinetic temperature found in the Sgr B2 envelope can be explained in terms of a C-shock chemistry (Flower, Pineau des Forêts, & Walmsley 1995). Martín-Pintado et al. (1999) proposed that these hot molecular shells are the shocked layers produced by the strong winds of W-R stars in the GC. The detection of warm $NH_3$ associated with the expanding shells produced by a W-R stellar wind supports the possible origin for the warm $NH_3$ in the Sgr B2 envelope. Although the densities in the GC clouds are certainly higher than the density in NGC 2359, the ammonia abundances and the expansion velocities in the GC shells are comparable to those found in NGC 2359.

Hot ammonia has also been observed in the nuclei of the external galaxies IC 342 (Martin & Ho 1986; Ho et al. 1990) and Maffei 2 (Henkel et al. 2000; Takano et al. 2000). The rotational temperatures of 50 and 80 K for IC 342 and Maffei 2, respectively, are similar to those observed in the GC. In both galaxy nuclei, the derived $NH_3$ abundances are also similar to the GC. Furthermore, the gas temperatures derived from $NH_3$ are higher than the dust temperature, and the nucleus of IC 342 has overall properties similar to those of the GC region (Downes et al. 1992). In both galactic nuclei, IC 342 and Maffei 2, the gas heating is not due to recently formed stars but to large-scale shocks. As in the case of the GC, the origin of such shocks remains unknown. Based on high angular resolution data (5″) from the nucleus of IC 342, Ho et al. (1990) conclude that the morphology of the $NH_3$ emission may be a distributed bump of small and hot molecular clouds surrounding young OB stars. However, the $NH_3$ is hard to be heated by the OB field radiation since it is easily photodissociated by the UV photons. It is worth noting that this ammonia distribution would also be consistent with hot shells like those observed by Martín-Pintado et al. (1999) in the GC. Further studies of the chemistry, physical conditions, and kinematics of the molecular gas in the environs of galactic evolved massive stars would provide important constraints to the models for the impact of the evolution of massive stars onto the interstellar medium.

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