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A CANDIDATE FOR THE EXCITING SOURCE OF THE POWERFUL MOLECULAR OUTFLOW NGC 2264G

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RESUMEN

Existe considerable controversia sobre cual es la fuente excitadora del poderoso flujo bipolar molecular NGC 2264G, en la nube molecular Monoceros OB1. Reportamos la detección, hecha con el *VLA* a 20 y 6-cm, de radio continuo proveniente de un objeto que proponemos como la fuente excitadora de dicho flujo. Esta fuente tiene un índice espectral de 0.7±0.2, consistente con un viento estelar ionizado. También detectamos en esa posición emisión de la transición $(J, K) = (1,1)$ del amoníaco y estimamos una masa de ~ 5 $M_\odot$ para el gas denso.

ABSTRACT

There is considerable controversy on the identification of the exciting source of the powerful bipolar molecular outflow NGC 2264G, in the Monoceros OB1 molecular cloud. We report the detection, made at 20 and 6-cm with the *VLA*, of radio continuum from an object that we propose as the exciting source of the outflow. The spectral index of this source is 0.7±0.2, consistent with an ionized stellar wind. We also detected at that position emission from the $(J, K) = (1,1)$ transition of ammonia and estimate the mass of the dense gas to be ~ 5 $M_\odot$.

Key words: INFRARED-SOURCES – NEBULAE-INDIVIDUAL – RADIO SOURCES-GENERAL – STARS-PRE-MAIN-SEQUENCE

I. INTRODUCTION

In a survey for high-velocity CO emission in the Monoceros OB1 molecular cloud, Margulis and Lada (1986) identified nine new possible outflow sources. The most remarkable one, called NGC 2264G by Margulis, Lada and Snell (1988), has a highly collimated bipolar morphology as well as considerably broad emission (CO is detected from -35 km s^{-1} to 54 km s^{-1}) and a large mechanical luminosity, $L_{mech} \simeq 2 - 20$ $L_\odot$. Even more remarkably, the outflow does not appear to be associated with any strong infrared source. The IRAS Point Source Catalog reports a source, IRAS 06384+0958, located at $\alpha(1950) = 06^h38^m25.5^s$; $\delta(1950) = 09°58'51''$, close to the centroid of the outflow. This IRAS point source is detected only at 60 μm with a modest flux of 6.3 Jy. Adopting a distance of 800 pc (Walker 1956) and the IRAS upper limits at 12, 25, and 100 μm, we obtain $L_{IRAS} \leq 10$ $L_\odot$. Hence, in this source we may have that the mechanical luminosity of the outflow could be comparable with the bolometric luminosity of the region, $L_{mech}/L_{bol} \simeq 1$, while in outflows it is typically found that $L_{mech}/L_{bol} \simeq 10^{-3}$ (Rodríguez *et al.* 1982). Clearly, as emphasized by Margulis *et al.* (1989), this is a remarkable outflow source that deserves further study, in particular concerning the identification of its exciting source and the determination of its parameters.

The detection and study of the exciting sources of outflows has been undertaken with a variety of techniques. In several well studied cases, such as L1551 (Bieging and Cohen 1985) and HH1-2 (Pravdo *et al.* 1985), the exciting source was detected by means of *VLA* observations of the associated radio continuum. In an attempt to identify better the exciting source of the NGC 2264G outflow we undertook *VLA* observations of the region. These *VLA* observations, as well as ammonia single-dish observations made at the Haystack Observatory, are described in §II. Our results and discussion are presented in §III and we summarize our conclusion in §IV.

II. OBSERVATIONS

a) *Continuum*

We made continuum observations of the NGC 2264G region at 6-cm (1988 August 26) and 20-cm (1988 December 19) using the *Very Large Array* of NRAO[3]. The 6-cm observations were made in the D configuration for an angular resolution of $\sim 10''$, while the 20-cm observations were made in the A configuration for an angular resolution of $\sim 1''$. The observations were made with an effective bandwidth of 100 MHz. The absolute amplitude calibrator was 3C286 for both frequencies and the phase calibrators were 0629+104 (for 6-cm) and 0735+178 (for 20-cm). The data were edited and calibrated using the standard *VLA* procedures.

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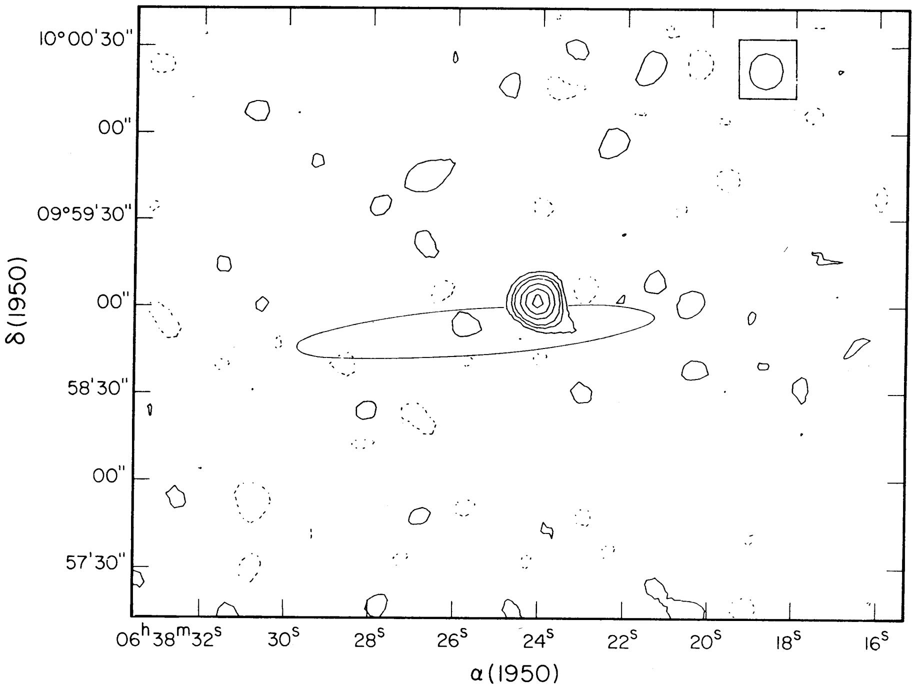

Fig. 1. Uniform-weighted, 6-cm *VLA* map of the radio source associated with the NGC 2264G outflow. The position error ellipsoid of IRAS 06384+0958 is shown at the center of the map. Contours are −1,1,2,3,5,7, and 9 times 0.19 mJy beam^{-1}. The half power contour of the beam is shown in the insert at the top right corner.

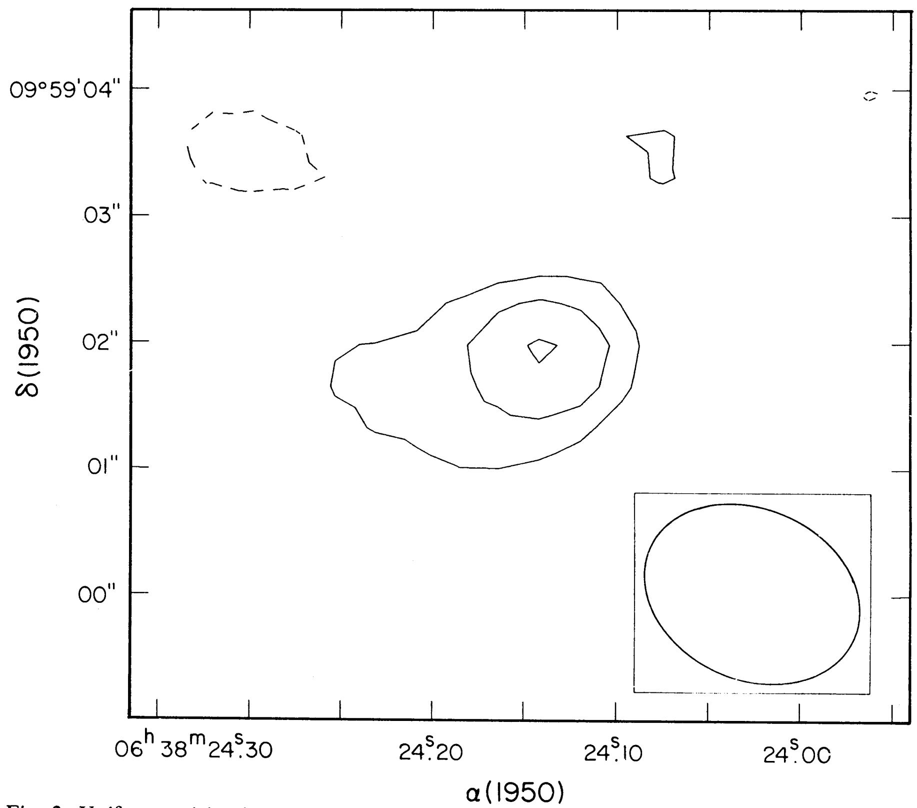

Fig. 2. Uniform-weighted, 20-cm *VLA* map of the radio source associated with the NGC 2264G outflow. Contours are −2,2,3, and 4 times 0.17 mJy beam^{-1}. The half power contour of the beam is also shown.

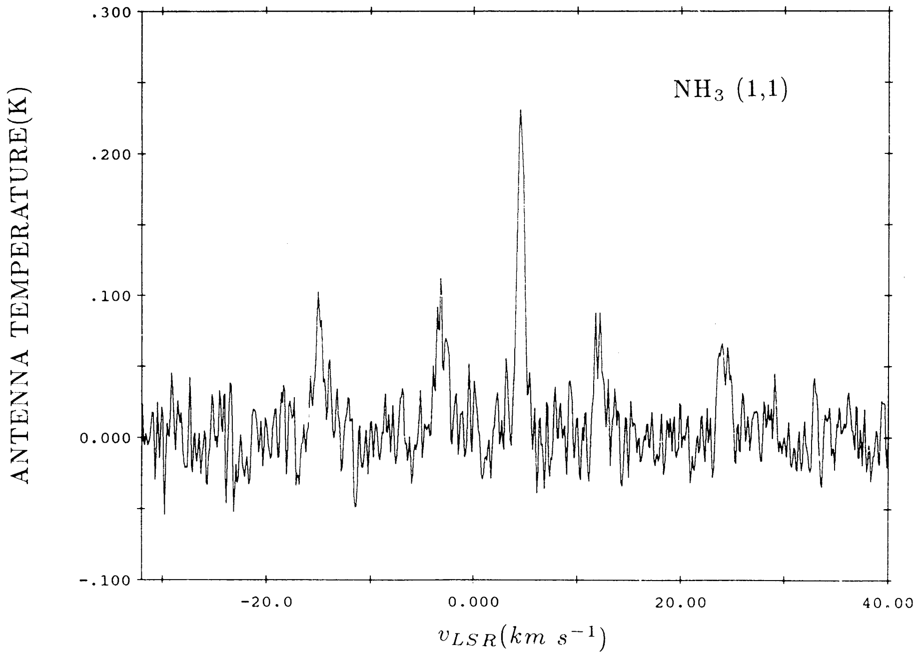

Fig. 3. Spectrum of the $(J, K) = (1,1)$ ammonia emission at the position of the radio source. The horizontal axis is radial velocity with respect to the local standard of rest and the vertical axis is the antenna temperature, corrected for atmospheric attenuation but uncorrected for beam efficiency.

We detected a continuum source, both at 6- and 20-cm (Figures 1 and 2), within the position error ellipsoid of IRAS 06384+0958. The source appears unresolved at 6- and 20-cm, and with flux densities of 1.9±0.2 and 0.8±0.2 mJy, respectively. The flux density dependence with frequency is $S_\nu \propto \nu^{0.7\pm0.2}$. The position of this radio continuum source, obtained from the 20-cm data, is $\alpha(1950) = 06^h38^m24.14^s\pm0.01^s$; $\delta(1950) = 09°59' 01.9''\pm0.2''$.

b) *Ammonia*

Observations of the $(J, K) = (1,1)$ inversion transition of ammonia were made during 1989 January using the 37-m radio telescope of the Haystack Observatory[4]. At 23.7 GHz, the beam efficiency is ∿ 0.32 and the beam size is 1.4′. We made a 9-point grid with full beam spacing centered at the position of the radio continuum source. The spectra were corrected for elevation-dependent gain variations and for atmospheric attenuation. Ammonia emission was detected only at the central position and the spectrum is shown in Figure 3. The parameters of the main line emission are peak antenna temperature, T_A = 0.23±0.02, full width at half maximum, Δv = 0.80±0.06 km s^{-1}, and radial velocity with respect to the local standard of rest, v_{LSR} = 4.60±0.03 km s^{-1}. The ratio of the main line peak emission to the inner satellite peak emission is 2.9±0.4.

4. Radio astronomy at Haystack Observatory of the Northeast Radio Observatory Corporation is supported by the National Science Foundation.

III. RESULTS AND DISCUSSION

We believe that the radio continuum source is associated with the exciting source of the NGC 2264G on the following arguments:

1) The *a priori* probability of finding a 6-cm source with a flux density of 1.9 mJy within the error ellipsoid of IRAS 06384+0958 is ∿ 0.003.

2) The spectral index of the source, 0.7±0.2, is consistent with the value of 0.6 expected for an ionized stellar wind (Panagia and Felli 1975).

3) The radio source is embedded in dense gas, as shown by the CS observations of Margulis *et al.* (1989) and our ammonia observations. The association with dense gas is known to be a characteristic of the energy sources of outflows (Torrelles *et al.* 1986; Anglada *et al.* 1989).

4) The radio continuum source is coincident, within observational error, with the infrared source IRS1, proposed by Margulis *et al.* (1989) as one of two candidate driving sources for the outflow. Furthermore, the radio source is located close to the center of the bipolar outflow (Figure 4). Most probably, IRS1, IRAS 06384+0958, and the *VLA* source are the same object.

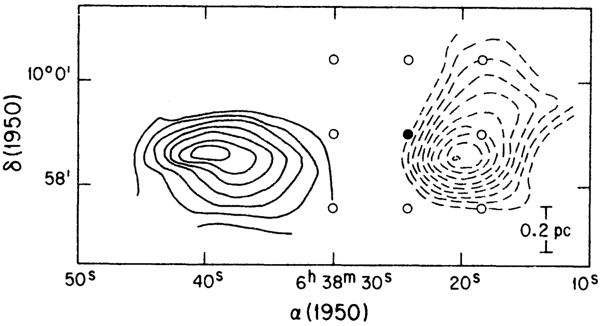

Fig. 4. Contour map of the redshifted (solid line) and blueshifted (dashed line) CO emission from NGC 2264G taken from Margulis, Lada and Snell (1988). The filled circle marks the position of the *VLA* source, where ammonia emission was detected. The empty circles mark the positions searched unsuccessfully for ammonia.

From the results of Margulis, Lada and Snell (1988), we estimate that the momentum rate in the outflow is $\dot{M}V \simeq 3 \times 10^{-3}$ $M_\odot$ yr^{-1} km s^{-1}. Assuming conservation of momentum rate and that the wind velocity is 300 km s^{-1}, we derive a mass loss rate of $\dot{M} \simeq 10^{-5}$ $M_\odot$ yr^{-1} for the star. If this wind were fully ionized, isotropic and with an electron temperature of 10^4 K, we would expect, from the formulation of Panagia and Felli (1975), a 6-cm flux of 26 mJy. This value is an order of magnitude larger than measured. An even larger radio continuum flux would be expected if the wind were collimated (Reynolds 1986). Two possible explanations for this discrepancy are:

1) The velocity of the wind is much larger than 300 km s^{-1}, about 1000 km s^{-1}. We consider this explanation unlikely since there is no evidence favoring that the winds of low-mass stars reach such high velocities.

2) The wind is largely neutral. This explanation was first discussed by Rodríguez and Cantó (1983) and it appears to be satisfactory at least for the case of HH7-11 (Lizano *et al.* 1988).

In any case, even the observed ionization rate cannot be produced by the low luminosity star associated with IRAS 06384+0958. The ionizing rate required by an ionized wind with an electron temperature of 10^4 K is (Felli and Panagia 1981):

$$\left[\frac{N_i}{s^{-1}}\right] \simeq 4.9 \times 10^{46} \left[\frac{S_\nu}{mJy}\right]^{1.5} \left[\frac{D}{kpc}\right]^{3} \left[\frac{\nu}{4.9\ GHz}\right]^{-0.9} \left[\frac{R_*}{10\ R_\odot}\right]^{-1}, \quad (1)$$

where S_ν is the observed flux at frequency ν, D is the distance to the source and R_* is the stellar radius assumed to be the inner radius of the ionized envelope. For a stellar radius of 2 $R_\odot$ we obtain $N_i \simeq 3 \times 10^{47}$, that could be provided by a B0 ZAMS star, with luminosity $\sim 3 \times 10^4$ $L_\odot$, about three orders of magnitude larger than observed. Even if we assume that all the luminosity of the ionizing source is in the form of 13.6 eV photons, we require an *ionizing* luminosity of $L_i \sim 3 \times 10^3$ $L_\odot$, still much larger than observed. We can lower the ionizing rate requirements by making the inner radius of the ionized envelope larger (see equation 1). However, we cannot make it very large because the centimeter continuum emission will become optically thin. The characteristic radius at which emission at a frequency ν arises is given by (Panagia and Felli 1975):

$$\left[\frac{R_\nu}{cm}\right] \simeq 5.7 \times 10^{14} \left[\frac{S_\nu}{mJy}\right]^{0.5} \left[\frac{\nu}{4.9\ GHz}\right]^{-1} \left[\frac{D}{kpc}\right]. \quad (2)$$

Since the emission at 4.9 GHz seems to follow the $\nu^{0.6}$ dependence of a wind, we can conclude that the inner radius of the ionized envelope must be equal or smaller than 6×10^{14} cm. This lowers the ionizing luminosity requirements to $L_i \geq 0.4$ $L_\odot$, compatible with the estimated luminosity for the source. We conclude that the ionization is, at least from the point of view of energetics, explainable if the ionization of the envelope starts very far from the stellar surface.

Other models to account for the radio continuum emission from low luminosity stars (Curiel, Cantó and Rodríguez 1987; Alonso-Costa and Kwan 1989) predict flat spectra in the cm range, in disagreement with what is observed in NGC 2264G.

Finally, we discuss the ammonia emission observed by us at the position of the radio source (Figure 3). The ratio of the main line peak emission to the inner satellite peak emission, 2.9±0.4, implies an optical depth for the main transition of $\tau_m = 0.6 \pm 0.4$, suggesting modest opacity. Assuming that the ammonia emission is optically thin and unresolved for our beam, with an excitation temperature of 10 K, and that $N(H_2)/N(NH_3) = 10^8$ (Herbst and Klemperer 1973), the mass in molecular hydrogen is given approximately by:

$$\left[\frac{M(H_2)}{M_\odot}\right] \simeq 7\,\frac{1}{\eta_A}\left[\frac{T_A}{K}\right] \left[\frac{\Delta v}{km\ s^{-1}}\right] \left[\frac{\theta_A}{1'}\right]^2 \left[\frac{D}{kpc}\right]^2, \quad (3)$$

where η_A and θ_A are the aperture efficiency and beam size of the antenna, and D is the distance. For Haystack,

$\eta_A \simeq 0.3$ and $\theta_A = 1.4'$. We then derive $M(H_2) \simeq 5\ M_\odot$ for the dense gas. This mass is in the range of values found for dense cores associated with molecular outflows (Torrelles *et al.* 1986; Anglada *et al.* 1989).

IV. CONCLUSIONS

We studied in the radio continuum and in the (1,1) transition of ammonia the core of the powerful outflow NGC 2264G. Our main conclusions are:

1) We detected 6- and 20-cm emission from a source that is proposed as the exciting source of the outflow. This radio source has a spectral index of 0.7±0.2, consistent with that expected for an ionized wind.

2) The radio continuum source is associated with IRS1, one of the two infrared sources proposed by Margulis *et al.* (1989) as candidates for driving the outflow. Most probably IRS1, IRAS 06384+0958, and the *VLA* radio source are the same object.

3) There is (1,1) ammonia emission at the position of the radio continuum source and we estimate a mass of $\sim 5\ M_\odot$ for the dense gas.

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