Revista Mexicana de Astronomía y Astrofísica, **45**, 273–277 (2009)

THE RADIO COUNTERPARTS TO THE BINARY O4+O4 SYSTEM CEN 1 IN NGC 6618, THE CLUSTER IONIZING M17

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Received 2009 July 8; accepted 2009 August 15

RESUMEN

Presentamos el análisis de una observación de archivo hecha en el año 2000 con el Very Large Array a 8.46 GHz hacia M17. En la región del cúmulo estelar NGC 6618 detectamos siete fuentes compactas de radio, de las cuales cuatro tienen contrapartes de rayos X en observaciones de Chandra. Dos de las fuentes de radio+rayos X coinciden posicionalmente con las dos estrellas O4 que forman el sistema binario CEN 1. Estas estrellas son las fuentes principales de ionización de la región H II M17 y los objetos más luminosos en rayos X de la zona. Las densidades de flujo observadas a 8.46 GHz exceden en un orden de magnitud los valores esperados para el caso de emisión libre-libre de un viento. Una observación adicional de archivo hecha en 1988 a 4.86 GHz sugiere variabilidad en las fuentes de radio asociadas a CEN 1.

ABSTRACT

We present the analysis of VLA archive observation made in the year 2000 at 8.46 GHz toward M17. In the region of the stellar cluster NGC 6618 we detect seven compact radio sources, of which four have Chandra X-ray counterparts. Two of the radio+X-ray sources coincide positionally with the two O4 stars that form the binary systen CEN 1. These stars are the main ionizing sources of the M17 H II region and the brightest X-ray objects in the zone. The observed 8.46 GHz flux densities exceed by an order of magnitude the values expected from free-free emission from a wind. An additional archive observation made in 1988 at 4.86 GHz suggests variability in the radio sources associated with CEN 1.

Key Words: stars: individual (CEN 1) — ISM: individual (M17) — radio continuum: stars

1. INTRODUCTION

Since O and Wolf-Rayet stars possess strong ionized winds, they have thermal (free-free) radio emission that can be detected as a compact source with sensitive interferometer observations (e.g., Leitherer, Chapman, & Koribalski 1995; Chapman et al. 1999; Güdel 2002). Assuming a steady, spherically symmetric wind, and having information on the terminal velocity of the wind it is possible to estimate the mass-loss rate (Olnon 1975; Panagia & Felli 1975; Wright & Barlow 1975).

However, time-variable, nonthermal (synchrotron) emission is also frequently present (Abbott, Bieging, & Churchwell 1984; Becker & White 1985; Persi et al. 1990), complicating the interpretation of the data. Since the wind is optically thick to radio emission out to hundreds of stellar radii, the nonthermal component must originate at such large distances from the star. Possible explanations for the nonthermal component include synchrotron emission from electrons accelerated in shocks of unstable winds of single stars (White 1985; Caillault et al. 1985), in colliding-wind shocks in massive binaries (Eichler & Usov 1993), and in the interaction zone between the thermal wind and a previously ejected shell (Leitherer, Chapman, & Koribalski 1997). The possibility of synchrotron emission in single O and WR stars has been discussed by van Loo, Runacres, & Blomme (2006), who conclude that this type of emission can be taken as evidence of a binary nature.

An important subset of the massive stars whose winds are potentially detectable in radio are the O

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stars that at present are ionizing their associated H II regions. In this case the mass loss rate derived from the radio observations could be compared with the expected effects in the surrounding medium (for example, in the presence of shocked regions and bubbles).

In this paper we present the analysis of archive 8.46 GHz continuum observations made with the Very Large Array (VLA) in the A configuration toward M17 (the Omega Nebula, NGC 6618, W38, S45) on 2000 December 08 (2000.94), as part of project AF374. From these observations we detect in the radio continuum at 3.6 cm several point sources that are located in the region of the NGC 6618 cluster. In particular, we detect the two components of the massive visual binary CEN 1 (Chini, Elsaesser, & Neckel 1980), that are separated by $\sim 1\rlap{.}''8$. This luminous source was detected by Kleinmann (1973), who classified it as a double O or early B system and it is believed to be the dominant source of ionizing photons in the region (e.g., Hoffmeister et al. 2008). Recently, Hoffmeister et al. (2008) showed that each component of this O4 V+O4 V binary star, named CEN 1a (NE component) and CEN 1b (SW component) by them, is itself composed of a spectroscopic binary system of nearly equal-mass components. From Chandra ACIS observation of the stellar populations in and around the M17 H II region, Broos et al. (2007) detected 886 X-ray sources; CEN 1a and CEN 1b are the brightest ones.

To gain a better understanding of the nature of the radio sources in the region, we also analyzed archive 4.86 GHz continuum observations made with the Very Large Array (VLA) in the AD configuration on 1988 October 09 (1988.77), as part of project AC233.

The physical association of CEN 1a and CEN 1b is still a matter of debate, since multicolor photometry indicates that CEN 1a and 1b are reddened by A_V=10 and 13 mag, respectively (Hoffmeister et al. 2008). Then, if CEN 1 is a physical binary system, this large difference can only be explained by a highly clumped interstellar medium along the line of sight. Following the discussion of Hoffmeister et al. (2008), we adopt a distance of 2.1±0.2 kpc for M17.

2. DATA REDUCTION

The archive data were edited and calibrated using the software package Astronomical Image Processing System (AIPS) of NRAO. The (u,v) data was self-calibrated in phase. Cleaned maps were obtained using the task IMAGR of AIPS and the ROBUST parameter (Briggs 1995) of this task set to 0, to optimize the compromise between angular resolution and sensitivity.

2.1. *8.46 GHz observations*

The amplitude calibrator used was 3C286, with an adopted flux density of 5.21 Jy and the phase calibrator was 1832−105, with a bootstrapped flux density of 1.36±0.01 Jy. To avoid contamination from the extended radio continuum emission present in the region, we used only spacings larger than 100 kλ, suppressing structures larger than $\sim 2''$. The final image had a synthesized beam of $0\rlap{.}''32 \times 0\rlap{.}''19$; PA $=-15°$.

The phase center of the observations was located at position $\alpha(2000) = 18^h\ 20^m 24\rlap{.}''838$; $\delta(2000) = -16°\ 11'\ 35\rlap{.}''13$, very close to the position of the most brilliant radio source in the region, the embedded ultracompact H II region M17-UC1, that has been studied in detail by Felli, Churchwell, & Massi (1984). Here, we concentrate our attention on the region of the stellar cluster NGC 6618, that ionizes M17. The center of this cluster is located $\sim 1\rlap{.}'5$ to the NE of the phase center of the observations and the images in the region of NGC 6618 show a radial bandwidth smearing of $\sim 0\rlap{.}''3$, comparable with the synthesized beam. Although this effect complicates the reliable determination of the angular size of the sources, it does not affect significatively their positions or flux densities.

2.2. *4.86 GHz observations*

The amplitude calibrator used was 3C286, with an adopted flux density of 7.28 Jy and the phase calibrator was 1733−130, with a bootstrapped flux density of 6.35±0.03 Jy.

To avoid contamination from the extended radio continuum emission present in the region, we used only spacings larger than 30 kλ, suppressing structures larger than $\sim 6''$. The final image had a synthesized beam of $1\rlap{.}''33 \times 0\rlap{.}''35$; PA $=+3°$. The phase center of the observations was located at position $\alpha(2000) = 18^h\ 20^m 34\rlap{.}''407$; $\delta(2000) = -16°\ 10'\ 10\rlap{.}''43$.

3. RESULTS

In the NGC 6618 region we detect at 8.46 GHz seven unresolved ($\leq 0\rlap{.}''3$) radio sources, whose positions and flux densities are given in Table 1. Four of the seven radio sources are associated with optical, X-ray or infrared sources previously reported and these associations are also listed in Table 1. The most interesting radio sources are those associated

TABLE 1

COMPACT 8.46 GHz RADIO SOURCES IN THE NGC 6618 REGION

	Position[a]		Total Flux	
VLA	α(J2000)	δ(J2000)	Density (mJy)	Counterpart[b]
1	18 20 29.82	−16 10 45.5	0.7±0.1	CEN 1b, CXOU J182029.81-161045.6, B+536
2	18 20 29.84	−16 10 15.2	1.3±0.1	—
3	18 20 29.90	−16 10 44.4	2.4±0.2	CEN 1a, 2MASS J18202986-1610449[c], B+543
4	18 20 30.01	−16 10 35.2	1.0±0.1	CXOU J182030.02-161034.8, B+554
5	18 20 30.58	−16 11 04.1	1.0±0.1	2MASS J18203057-1611040
6	18 20 30.78	−16 10 59.3	1.1±0.1	—
7	18 20 33.07	−16 11 21.5	0.8±0.1	CEN 43, 2MASS J18203306-1611215, B+675

[a]Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds. Positional accuracy is estimated to be $0.''2$.

[b]CEN = Chini et al. 1980; CXOU = Chandra X-ray Observatory Unregistered source; B+ = Broos et al. (2007); 2MASS = Two Micron All-Sky Survey.

[c]The 2MASS observations do not resolve the components 1a and 1b and this source can be considered as a counterpart of both components.

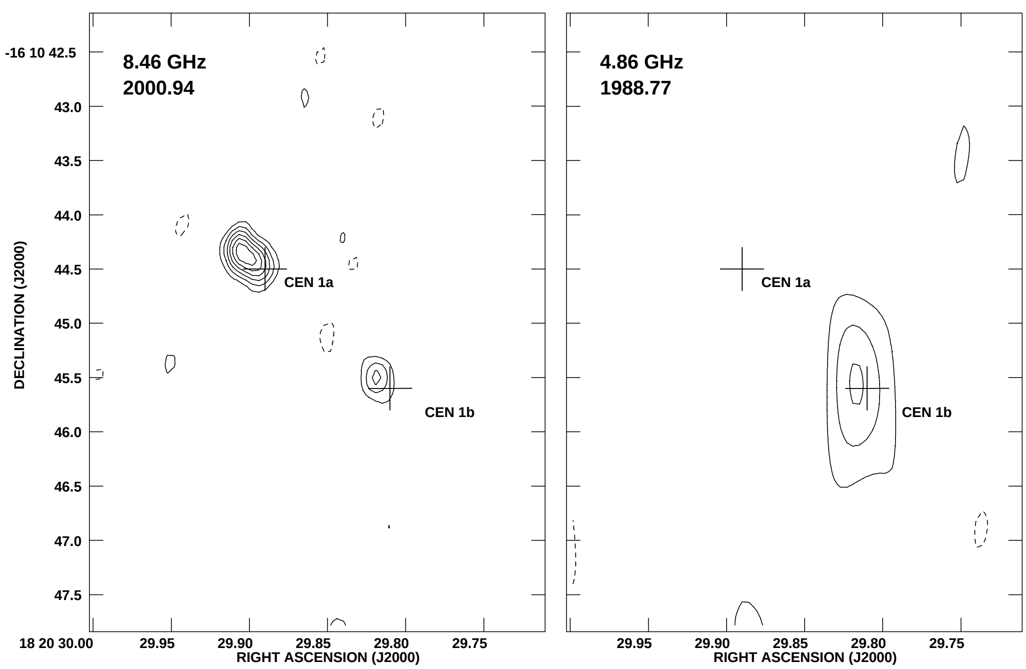

Fig. 1. (Left) Contour images of the 8.46 GHz continuum emission from the CEN 1 region. The two radio sources detected coincide, within the positional error, with the optical, infrared, and X-ray sources CEN 1a and 1b. The crosses mark the X-ray positions given by Broos et al. (2007). We have associated an error of $0.''2$ to the X-ray observations. The contours are −3, 3, 6, 9, 12, 15, and 18 times 60 μJy beam^{-1}. (Right) Contour images of the 4.86 GHz continuum emission from the CEN 1 region. The contours are −3, 3, 6, and 9 times 130 μJy beam^{-1}.

with CEN 1a and 1b, and are shown in Figure 1. As can be seen in this figure, the X-ray positions of Broos et al. (2007) and our radio positions have what appears to be a small ($\sim 0.''2$) systematic displacement. We attribute this displacement to the positional errors of the radio and X-ray observations and assume in our discussion that the radio and X-ray sources are associated.

At 4.86 GHz we detect only two of the radio sources detected at 8.46 GHz: VLA 1 (=CEN 1b)

TABLE 2

COMPACT 4.86 GHz RADIO SOURCES IN THE NGC 6618 REGION

VLA	Position[a] α(J2000)	δ(J2000)	Total Flux Density (mJy)	Counterpart[b]
1	18 20 29.81	−16 10 45.6	1.5±0.2	CEN 1b, CXOU J182029.81-161045.6, B+536
7	18 20 33.06	−16 11 21.6	1.7±0.2	CEN 43, 2MASS J18203306-1611215, B+675

[a]Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds. Positional accuracy is estimated to be $0.''4$.

[b]CEN = Chini et al. 1980; CXOU = Chandra X-ray Observatory Unregistered source; 2MASS = Two Micron All-Sky Survey.

and VLA 7. The positions and flux densities of these two sources are given in Table 2. In Figure 1 we show the 4.86 GHz image for the CEN 1a and 1b region. It is remarkable that at this frequency we do not detect, at a 4-σ upper limit of 0.8 mJy, the source VLA 3 (=CEN 1a) which in 2000 was, with 2.4 mJy, the brightest compact radio source in the region at 8.46 GHz. This result suggests time variablity, at least for the radio source associated with CEN 1a.

4. DISCUSSION

An O4 V star has a temperature of 5.0×10^4 K, a luminosity of 1.3×10^6 $L_\odot$, a radius of 15 $R_\odot$, and an ionizing photon rate of 8.5×10^{49} s^{-1} (Thompson 1984). Its mass is estimated to be $\sim$60 $M_\odot$ (Crowther 2004). Following Kudritzki & Puls (2000) we find that on the average they have a wind terminal velocity of $v_\infty = 3.0 \times 10^3$ km s^{-1} and a mass loss rate of $\dot{M} = 3.9 \times 10^{-6}$ $M_\odot$ yr^{-1}.

Using these wind parameters, we estimate the free-free radiation (at radio wavelengths) from a completely ionized spherical wind assuming an electron temperature in the wind of 10^4 K (Panagia & Felli 1975; Wright & Barlow 1975). At 8.46 GHz, we derive an expected flux density of $\sim$0.1 mJy. This is almost an order of magnitud below the detected values in CEN 1a and we tentatively conclude that the thermal emission from a simple wind model cannot explain the observations.

Radio observations of massive binary stars (e.g., Moran et al. 1989; Dougherty, Williams, & Pollacco 2000; Dougherty et al. 2005) have revealed the presence of strong shocks formed from the collision of the two stellar winds, the so-called wind-collision region (WCR). Numerical models developed by Pittard et al. (2006; see also Dougherty et al. 2003) show that the flow within the WCR may emit both free-free and synchrotron radiation. They investigate how the emission varies with binary separation and viewing angles. For the thermal component, they find that the contribution by the WCR to the total spectrum (from the stellar winds and the shocked gas) increases as the binary separation decreases. Consequently, a complex, composite spectrum, usually interpreted as evidence of non-thermal emission, can result in some cases entirely from free-free processes. Nevertheless, the adopted system parameters of the colliding wind binary CEN 1a (assuming identical stellar winds) and the variability observed between 1988 and 2000 suggest that the nature of the emission is synchrotron.

Eichler & Usov (1993) considered the generation of non-thermal radio emission in binaries composed of early-type stars. They show that non-thermal emission arises from the site of the stellar wind collision and the expected value of the luminosity depends on the binary separation (see also, Pittard et al. 2006). For synchrotron emission to be observed, the wind collision region must be outside the optically thick region of the stellar winds. Following the formulation of Eichler & Usov (1993), we estimated the expected intrinsic non-thermal flux density for the binary system CEN 1a. Assuming a total mass of 120 $M_\odot$, a radial velocity difference of $\sim$ 250 km s^{-1} (from the spectroscopy of Hoffmeister et al. 2008), and a circular orbit, we estimate a separation between the components of the binary of D= 1.7 AU.

We estimated the order of magnitude of the magnetic field at the wind collision region as follows. From analogy with 9-Sgr, a star with the same spectral type (O4V; Rauw et al. 2002) as CEN 1 and using the formulation for the strength of the magnetic field in the outflowing gas (Eichler & Usov 1993), we obtain a value of $B \simeq 1$ G. Under these assumptions, the expected intrinsic 8.4 GHz flux density is $S_\nu \simeq 1$ Jy, which is much higher than the observed value ($\sim$ 2.4 mJy). Hence, a clear reduction in the amount of synchrotron emission is required. According to Panagia & Felli (1975) and Wright & Barlow (1975), the radius of the optically thick region of the stellar winds at this frequency is $R_\nu \simeq 10^{14}$ cm ($\sim$7 AU $>$ D), and then, the free-free absorption on the synchrotron emission could explain this reduction. The variability observed between 1988 and 2000 also suggests that the nature of the emission is synchrotron. It is well established (e.g., White & Becker 1995) that the synchrotron emission associated with massive binary stars strongly depends on the separation between the stars and can exhibit periodic variability for eccentric orbits and we suggest that CEN 1a could exhibit periodic radio variability.

A detailed study of the spectral index, polarization, and time variability is required to establish the emission mechanisms present in the components of the multiple CEN 1 system.

5. CONCLUSIONS

Our main conclusions are as follows.

(1) We report the detection of seven compact radio sources in the region of NGC 6618, the cluster ionizing M17. From their association with optical, infrared, and X-ray objets, these radio sources most probably trace stars of the cluster.

(2) Two of these sources are associated with CEN 1a and CEN 1b, respectively. These sources are the components of the optical binary CEN 1, separated in the sky by $1''\!.8$.

(3) The flux densities observed from CEN 1a and CEN 1b exceed the expected free-free emission from the massive stars associated with them. This discrepancy is particularly strong in the case of CEN 1a. Both CEN 1a and CEN 1b are themselves composed of spectroscopic binaries and we propose that the observed emission could have a synchrotron nature, originating from the wind-collision region, although strongly absorbed by the free-free opacity of the stellar winds. The variability observed in CEN 1a also suggests a synchrotron origin for the radio emission and it could exhibit periodic behavior if due to an eccentric orbit. If the non thermal nature of the radio emission is confirmed, this will support the conclusion of van Loo et al. (2006) that this emission is systematically associated with close binary systems.

We thank an anonymous referee for helpful comments. We are also thankful for the support of DGAPA, Universidad Nacional Autónoma de México, and of Conacyt (Mexico). This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Abbott, D. C., Bieging, J. H., & Churchwell, E. 1984, ApJ, 280, 671
Becker, R. H., & White, R. L. 1985, ApJ, 297, 649
Briggs, D. 1995, PhD thesis, New Mexico Inst. of Mining and Technology
Broos, P. S., et al. 2007, ApJS, 169, 353
Caillault, J.-P., et al. 1985, Nature, 313, 376
Chapman, J. M., Leitherer, C., Koribalski, B., Bouter, R., & Storey, M. 1999, ApJ, 518, 890
Chini, R., Elsaesser, H., & Neckel, T. 1980, A&A, 91, 186
Crowther, P. A. 2004, in Evolution of Massive Stars, Mass Loss and Winds, ed. M. Heydari-Malayeri, Ph. Stee, & J. P. Zahn, 1
Dougherty, S. M., Beasley, A. J., Claussen, M. J., Zauderer, B. A., & Bolingbroke, N. J. 2005, ApJ, 623, 447
Dougherty, S. M., Pittard, J. M., Kasian, L., Coker, R. F., Williams, P. M., & Lloyd, H. M. 2003, A&A, 409, 217
Dougherty, S. M., Williams, P. M., & Pollacco, D. L. 2000, MNRAS, 316, 143
Eichler, D., & Usov, V. 1993, ApJ, 402, 271
Felli, M., Churchwell, E., & Massi, M. 1984, A&A, 136, 53
Güdel, M. 2002, ARA&A, 40, 217
Hoffmeister, V. H., Chini, R., Scheyda, C. M., Schulze, D., Watermann, R., Nürnberger, D., & Vogt, N. 2008, ApJ, 686, 310
Kleinmann, D. E. 1973, Astrophys. Lett., 13, 49
Kudritzki, R.-P., & Puls, J. 2000, ARA&A, 38, 613
Leitherer, C., Chapman, J. M., & Koribalski, B. 1995, ApJ, 450, 289
__________. 1997, ApJ, 481, 898
Moran, J. P., Davis, R. J., Spencer, R. E., Bode, M. F., & Taylor, A. R. 1989, Nature, 340, 449
Olnon, F. M. 1975, A&A, 39, 217
Panagia, N., & Felli, M. 1975, A&A, 39, 1
Persi, P., Tapia, M., Rodriguez, L. F., Ferrari-Toniolo, M., & Roth, M. 1990, A&A, 240, 93
Pittard, J. M., Dougherty, S. M., Coker, R. F., O'Connor, E., & Bolingbroke, N. J. 2006, A&A, 446, 1001
Rauw, G., et al. 2002, A&A, 394, 993
Thompson, R. I. 1984, ApJ, 283, 165
van Loo, S., Runacres, M. C., & Blomme, R. 2006, A&A, 452, 1011
White, R. L. 1985, ApJ, 289, 698
White, R. L., & Becker, R. H. 1995, ApJ, 451, 352
Wright, A. E., & Barlow, M. J. 1975, MNRAS, 170, 41

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