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RADIO CONTINUUM SOURCES ASSOCIATED WITH AB AUR

Luis F. Rodríguez,[1] Luis Zapata,[1,2] and Paul T. P. Ho[3,2]

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RESUMEN

Presentamos observaciones de alta resolución angular y alta sensitividad, hechas con el Very Large Array a 3.6 cm, de la estrella Ae de Herbig AB Aur. Esta estrella es de interés porque su disco circunestelar muestra características que se han atribuido a la presencia de una compañera de baja masa o de un planeta gaseoso gigante, aún sin detectar. Nuestra imagen confirma la emisión de continuo que se sabe existe en asociación con la estrella, y detecta una débil protuberancia que se extiende aproximadamente $0\farcs3$ al SE de la estrella. Consideraciones teóricas y resultados observacionales previos son consistentes con la presencia de una compañera de AB Aur con la separación y ángulo de posición derivados de nuestros datos de radio. También determinamos los movimientos propios de AB Aur comparando nuestras nuevas observaciones con datos tomados 17 años atrás, y encontramos valores consistentes con los determinados por Hipparcos.

ABSTRACT

We present high angular resolution, high-sensitivity Very Large Array observations at 3.6 cm of the Herbig Ae star AB Aur. This star is of interest since its circumstellar disk exhibits characteristics that have been attributed to the presence of an undetected low mass companion or giant gas planet. Our image confirms the continuum emission known to exist in association with the star, and detects a faint protuberance that extends about $0\farcs3$ to its SE. Previous theoretical considerations and observational results are consistent with the presence of a companion to AB Aur with the separation and position angle derived from our radio data. We also determine the proper motion of AB Aur by comparing our new observations with data taken about 17 years ago and find values consistent with those found by Hipparcos.

Key Words: **BINARIES: VISUAL — RADIO CONTINUUM: STARS — STARS: EMISSION-LINE, BE — STARS: FORMATION — STAR: MASS LOSS**

1. INTRODUCTION

AB Aurigae (HD 31293) is one of the nearest Herbig Ae stars. It has a spectral type A0-A1 (Hernández et al. 2004) and from the Hipparcos parallax measurements (van den Ancker et al. 1998) it is known to be located at a distance of $D = 144\pm^{23}_{17}$ pc.

This star has received significant attention lately since its circumstellar disk (Mannings & Sargent 1997; Grady et al. 1999) was found to exhibit complex spiral-like structures in the near-IR continuum (Fukugawa et al. 2004), as well as in millimeter observations of molecular lines and continuum (Corder, Eisner, & Sargent 2005; Piétu, Guilloteau, & Dutrey 2005; Lin et al. 2006). Corder et al. (2005) estimate the outer radius of the disk to be $\sim$ 600 AU. In their CO and continuum observations of AB Aur at 3 and 1.3 mm Piétu et al. (2005) found that the disk also has non-Keplerian motions and an inner hole about 70 AU in radius, and proposed as a possible explanation for these peculiar disk characteristics the presence of a low mass companion located about 40 AU from AB Aur. Lin et al. (2006) also find non-Keplerian motions in the disk and the presence of a central depression, and suggest that these dynami-

[1] Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Morelia, Mexico.
[2] Harvard-Smithsonian Center for Astrophysics, MA, USA.
[3] Academia Sinica, Institute of Astronomy and Astrophysics, Taipei, Taiwan.

cal perturbations could be produced by the possible existence of a giant planet forming in the disk.

However, a number of optical and infrared studies place stringent mass limits on a companion to AB Aur. As discussed by Piétu et al. (2005), these limits depend on the distance of the companion to the star (the closer the companion is, the harder it is to detect from imaging because of the bright stellar emission at optical and infrared wavelengths, and thus the higher the upper limit). From the near-infrared speckle observations of Leinert et al. (1994), Piétu et al. (2005) estimate upper mass limits for a possible companion in the range of 0.01 to 0.3 $M_\odot$ for distances between 140 to 10 AU ($1''\!.0$ to $0''\!.07$).

In this paper we present sensitive, high angular resolution 3.6 cm continuum observations made with the Very Large Array (VLA) in an attempt to search for a radio companion to AB Aur. Stellar emission at radio wavelengths is faint, and the detection of such a companion would help us to understand the peculiarities of disk. Our search for radio continuum emission from a possible companion to AB Aur is justified since some brown dwarfs have been observed as radio sources (e. g. Berger et al. 2005) and it has also been speculated that giant gas planets could be sources of detectable emission at radio wavelengths (Farrell et al. 2004).

2. OBSERVATIONS

The observations were taken on 2006 April 28 with the VLA of the NRAO[4] at 3.6 cm in the A configuration. We observed for a total of 10 hours with an effective bandwidth of 100 MHz and both circular polarizations. The absolute amplitude calibrator was 1331+305 (with an adopted flux density of 5.21 Jy), while the phase calibrator was 0443+346, with a bootstrapped flux density of 0.581±0.005 Jy. The data were edited and calibrated using the software package Astronomical Image Processing System (AIPS) of NRAO. Cleaned maps were obtained using the task IMAGR of AIPS and the ROBUST parameter (Briggs 1995) of this task set to 5, to optimize sensitivity.

3. RESULTS

3.1. *Main source and protuberance*

A source was detected in association with AB Aur (see Figure 1). Three other sources were detected within a few arcmin of AB Aur, none of them with known counterparts at other wavelengths. The parameters of the four sources detected are given in Table 1. The deconvolved dimensions of the sources were obtained fitting them with Gaussian ellipsoids using the task IMFIT of AIPS and the fits were made taking into account the effect of bandwidth smearing for the sources away from the phase center. The sources VLA 1, 2, and 4 show extended dimensions at the scale of $0''\!.3$ on one axis. The source VLA 2 is the one associated with AB Aur and will be discussed in detail below. The small elongations observed in VLA 1 and 4 could indicate that they are remote radio galaxies that will appear as elongated because of their jet and lobe structures. However, part of the elongation could be due to the effect of bandwidth smearing not being fully corrected by the task IMFIT. Since VLA 2 is at the center of the field, it is not affected by bandwidth smearing and its elongation is considered to be real.

The presence of weak centimeter radio emission in association with AB Aur has been previously reported by Güdel et al. (1989) and Skinner, Brown, & Stewart (1993). The total flux density measured by us, 0.20±0.03 mJy, is consistent within the noise of the observations with the values reported previously at the same wavelength. However, this is the first time that the image obtained is sensitive enough to show the possible presence of structure in the radio emission. The faint protuberance to the SE of AB Aur in the 3.6 cm image shown in Figure 1 is most likely real since it is at the modest but significant level of 4-σ and since a similar structure at the same position angle, separation, and brightness is not present in any of the other three sources in the field (as it would be expected if the feature were due to some anomalous phase error effect). We have also checked the presence of the structure with self-calibration made with long integration periods and the result makes us confident that the feature presented in Figure 1 is real.

As can be seen in Figure 1, the main emission peak of the radio source coincides within error with the Hipparcos position from Perryman et al. (1997), corrected for the proper motion reported by these authors. Once we subtract in the (u,v) plane a point source with the flux and position of the radio peak component, we are left with a faint component displaced about $0''\!.3$ to the SE of AB Aur (see bottom panel in Figure 1). The position and flux density of this possible source are given in Table 1. We note that the flux observed by us ($\sim$70 μJy) is much larger than the flux density of $\sim$0.4 μJy expected from a brown dwarf as LP944-20 (Berger et al. 2001), if located at the same distance as AB Aur.

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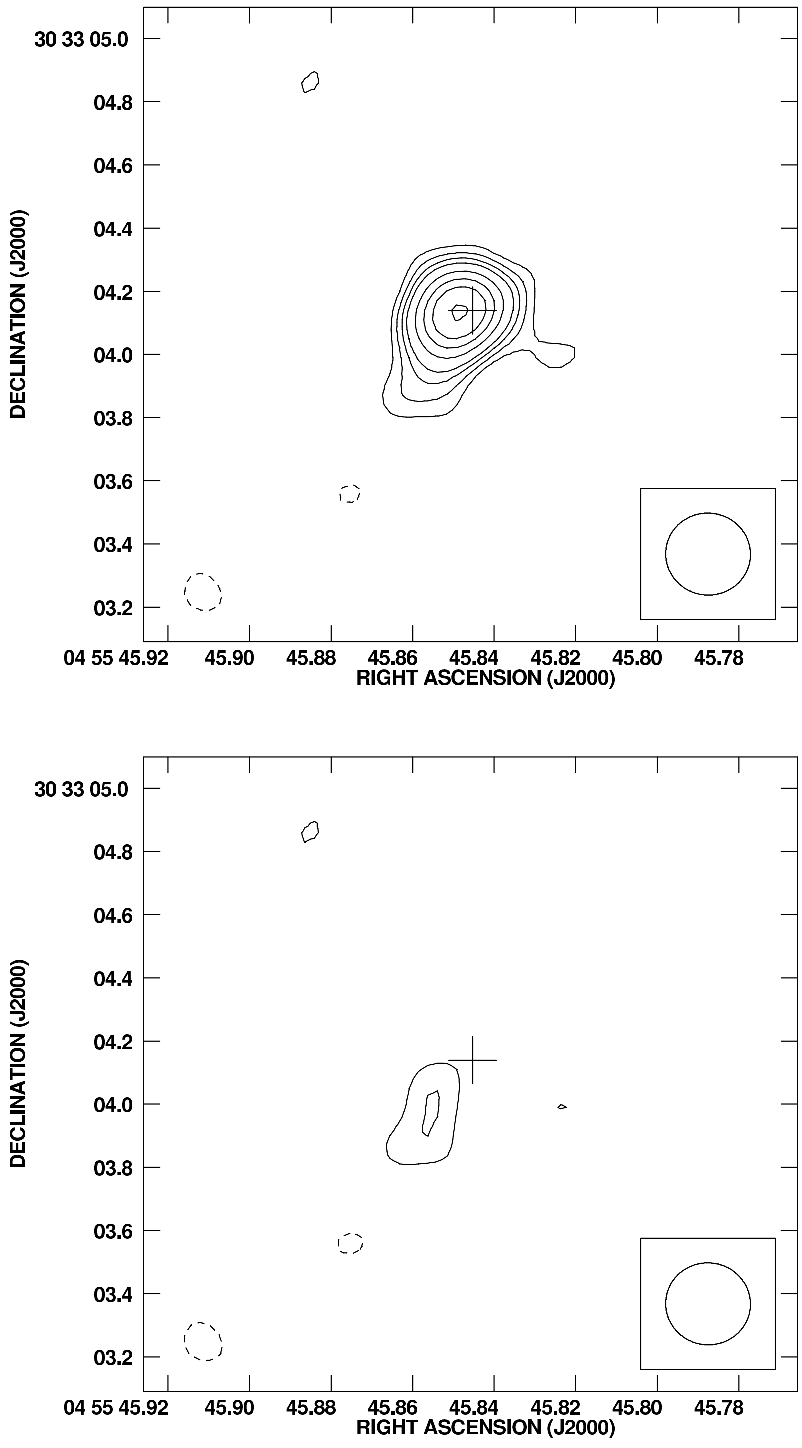

Fig. 1. (Top) Contour image of the 3.6 cm continuum emission from AB Aur. (Bottom) Contour image of the 3.6 cm continuum emission from AB Aur with a point source at the position of the radio peak subtracted in the *(u,v)* plane. Note the residual emission in this image. The contours are -4, -3, 3, 4, 5, 6, 8, 10, and 12 times 9.3 μJy, the rms noise of the image. The cross marks the Hipparcos position of AB Aur, corrected for proper motion. The positional error of Hipparcos for AB Aur is $\sim 0.''015$, taking into account the errors in absolute position and in the correction for proper motion. The size of the cross is five times larger for clarity. The half power contour of the beam ($0.''27 \times 0.''26$; $PA = +84^\circ$), is shown at the bottom right corner.

TABLE 1

RADIO SOURCES IN THE FIELD OF AB AUR

VLA	Position[a] α(J2000)	Position[a] δ(J2000)	Total Flux Density (mJy)	Deconvolved Angular Size[b]	Counterpart
1	04 55 42.085	+30 33 26.94	0.22±0.04	$0.''33 \pm 0.''08 \times < 0.''2$; $43° \pm 25°$	–
2	04 55 45.849	+30 33 04.12	0.20±0.03	$0.''27 \pm 0.''03 \times < 0.''1$; $139° \pm 12°$	AB Aur
3	04 55 45.855	+30 33 03.96	0.07±0.02	$\sim 0.''2$	Companion?
4	04 55 47.397	+30 34 34.90	0.54±0.04	$0.''22 \pm 0.''03 \times < 0.''1$; $19° \pm 6°$	–
5	04 55 47.541	+30 32 00.52	0.13±0.03	$< 0.''2$	–

[a]Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds. Absolute positional accuracy is estimated to be $0.''02$.

[b]Major axis × minor axis; position angle.

3.2. *Possible explanations for the nature of the radio protuberance*

There are at least two possible explanations for the presence of the faint protuberance in the radio image of AB Aur. The first is that we are seeing ionized, collimated gas flowing along the position angle of ∼139°. Thermal jets, which are ionized outflows detected at radio wavelengths via their free-free emission (e.g. Anglada 1996; Rodríguez 1997), are fairly common in young stars. Furthermore, the position angle of the feature ($139° \pm 12°$) is nearly perpendicular to the position angle of the major axis of the disk (∼66°), as determined from the millimeter observations of Lin et al. (2006). This relative orientation is expected in models in which the magnetic fields of the disk help accelerate and collimate the jet. On the other hand, there is no evidence of optical jets (Grady et al. 1999) or molecular outflows (Cantó et al. 1983; Levreault 1988) in association with AB Aur. This may be due to the fact that AB Aur is a star for which DeWarf et al. (2003) estimate an age in the range of 1 to 4 million years. By this age, it is believed that strong outflow activity is no longer present in young stars (Mundt, Brugel, & Bührke 1987) and we consider this explanation unlikely.

A second possibility is that we are observing a faint radio companion to AB Aur. In this case, the emission would most probably be of gyrosynchrotron nature, as observed in young stars with active magnetospheres (Güdel 2002). This hypothetical companion would be located at about $0.''3$ from AB Aur, which corresponds to a distance of about 40 AU. Remarkably, this is the separation proposed by Piétu et al. (2005) on dynamical considerations based on the size of the central hole in the disk. Optical and infrared searches with high angular resolution and sensitivity at this position could be worthwhile.

Another interesting result that supports the presence of a companion at the position of the radio protuberance is that presented by Baines et al. (2006). These authors did high-resolution optical spectro-astrometry of AB Aur and concluded that it has a companion located at a position angle of 146°, a value very close to that determined by us for the radio protuberance (139°). Baines et al. (2006) also set a lower limit to the separation of $0.''026$, consistent with the separation measured by us. However, it should be noted that Baines et al. (2006) favor a value of $0.''5$ for the separation and that this value would be inconsistent with our results.

Unfortunately, it is difficult to be sure of the reality of the protuberance. This structure is very faint and is below the sensitivity of previous images. Observations at several wavelengths with high sensitivity are required but this is not feasible now, at least within reasonable integration times. We will have to wait for several years to confirm or refute the presence of a faint radio companion to AB Aur, once the more sensitive Expanded Very Large Array is completed.

3.3. *Radio Proper Motions*

Finally, we use our new position and that obtained from a reanalysis of the available VLA archive data in the A configuration for 1988 October 7 and 27 and 1990 February 10 and 12 to search for proper motions in the radio source associated with AB Aur. Our observations correspond to the epoch 2006.32, while those of the archive data are taken to have an average epoch of 1989.46. The position of the source for this earlier epoch is $\alpha(2000) = 04^h\ 55^m\ 45\overset{s}{.}839$; $\delta(2000) = 30^\circ\ 33'\ 04\overset{''}{.}59$. Comparing with the position given in Table 1 and taken into account that the time difference between observations is of 16.86 years, we derive proper motions of $\mu_\alpha = +8 \pm 5$ mas yr^{-1} and $\mu_\delta = -28 \pm 5$ mas yr^{-1}. These values are in agreement (although they have significantly less signal-to-noise ratio) with those reported by Hipparcos (Perryman et al. 1997): $\mu_\alpha = +1.71 \pm 1.06$ mas yr^{-1} and $\mu_\delta = -24.24 \pm 0.67$ mas yr^{-1}. The near coincidence between the radio and optical positions shown in Figure 1 also indicates the agreement of the radio and optical astrometries.

Two of the remaining sources listed in Table 1 were detected in both the 1989.46 and 2006.32 images. The first source is VLA 1, that for the 1989.46 epoch has a position of $\alpha(2000) = 04^h\ 55^m\ 42\overset{s}{.}088$; $\delta(2000) = 30^\circ\ 33'\ 26\overset{''}{.}85$, about $0\overset{'}{.}9$ to the west of AB Aur. Comparing with the position given in Table 1, we derive proper motions of $\mu_\alpha = -2 \pm 3$ mas yr^{-1} and $\mu_\delta = +5 \pm 3$ mas yr^{-1}. The other source is VLA 3, that for the 1989.46 epoch has a position of $\alpha(2000) = 04^h\ 55^m\ 47\overset{s}{.}398$; $\delta(2000) = 30^\circ\ 34'\ 34\overset{''}{.}91$, about $1\overset{'}{.}5$ to the north of AB Aur. Again, comparing with the position given in Table 1, we derive proper motions of $\mu_\alpha = -1 \pm 2$ mas yr^{-1} and $\mu_\delta = -1 \pm 2$ mas yr^{-1}. Thus, in constrast to the radio source associated with AB Aur that shows clear proper motions, the measurements of VLA 1 and 4 are consistent with no significant proper motions, which supports the possibility that they are extragalactic sources.

4. CONCLUSIONS

Our main conclusions are as follows.

(1) We obtained a high angular resolution, high sensitivity 3.6 cm image of AB Aur. Besides the emission associated with the star, which was previously known, we detect a faint protuberance to the SE of the star that could be tracing either a collimated outflow or possibly a low mass companion or even a giant gas planet. In the case of a companion, the separation measured by us ($0\overset{''}{.}3$) is consistent with that proposed by Piétu et al. (2005) from dynamical considerations on the size of the central hole in the disk. Furthermore, the position angle measured by us for the possible companion (139°) is very similar to that determined by Baines et al. (2006) from high-resolution optical spectro-astrometry of AB Aur. However, the emission is faint and requires confirmation with future, more sensitive facilities.

(2) Comparing with data taken about 17 years before, we can determine in the radio wavevelengths the proper motion of AB Aur, which is consistent with that measured with Hipparcos. In contrast, two other sources in the surroundings (VLA 1 and VLA 4) show no detectable proper motions, suggesting they are background extragalactic sources.

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Paul T. P. Ho: Academia Sinica, Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 106, Taiwan (pho@asiaa.sinica.edu.tw) and Harvard-Smithsonian Center for Astrophysics and Submillimeter Array, 60 Garden Street, Cambridge, MA 02138, USA (ho@cfa.harvard.edu).

Luis F. Rodríguez and Luis Zapata: Centro de Radiostronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 3-72, (Xangari), 58089 Morelia, Michoacán, Mexico (l.rodriguez, l.zapata@astrosmo.unam.mx).