AN IONIZED OUTFLOW FROM AB AUR, A HERBIG AE STAR WITH A TRANSITIONAL DISK

LUIS F. RODRÍGUEZ1,2, LUIS A. ZAPATA1, SERGIO A. DZIB3, GISELA N. ORTIZ-LEÓN1,
LAURENT LOINARD3, ENRIQUE MACÍAS3, AND GUILLÉM ANGLADA4

1 Centro de Radioastronomía y Astrofísica, UNAM, Apdo. Postal 3-72 (Xangari), 58089 Morelia, Michoacán, México; l.rodriguez@crya.unam.mx
2 Astronomy Department, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia
3 Max Planck Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
4 Instituto de Astrofísica de Andalucía (CSIC), Apartado 3004, E-18080 Granada, Spain

Received 2014 August 8; accepted 2014 August 27; published 2014 September 9

ABSTRACT

AB Aur is a Herbig Ae star with a transitional disk. Transitional disks present substantial dust clearing in their inner regions, most probably because of the formation of one or more planets, although other explanations are still viable. In transitional objects, accretion is found to be about an order of magnitude smaller than in classical full disks. Since accretion is believed to be correlated with outflow activity, centimeter free–free jets are expected to be present in association with these systems, at weaker levels than in classical protoplanetary (full) systems. We present new observations of the centimeter radio emission associated with the inner regions of AB Aur and conclude that the morphology, orientation, spectral index, and lack of temporal variability of the centimeter source imply the presence of a collimated, ionized outflow. The radio luminosity of this radio jet is, however, about 20 times smaller than that expected for a classical system of similar bolometric luminosity. We conclude that centimeter continuum emission is present in association with stars with transitional disks, but at levels than are becoming detectable only with the upgraded radio arrays. On the other hand, assuming that the jet velocity is 300 km s\(^{-1}\), we find that the ratio of mass loss rate to accretion rate in AB Aur is \(\sim 0.1\), similar to that found for less evolved systems.

Key words: ISM: jets and outflows – radio continuum: stars – stars: individual (AB Aur) – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

A significant fraction (\(\sim 20\%\); Andrews et al. 2011) of the millimeter-bright disk population shows a dust-depleted cavity around the central star. These cavities were first indirectly inferred from the infrared spectra of the star-disk system (e.g., Strom et al. 1989; Calvet et al. 2002; D’Alessio et al. 2005; Kim et al. 2013) and more recently spatially resolved in images at infrared (e.g., Geers et al. 2007) and millimeter wavelengths (e.g., Brown et al. 2009; Andrews et al. 2011; van der Marel et al. 2013; Pérez et al. 2014). These disks are referred to as transitional disks since the cavity could have been created by dynamical clearing due to tidal interactions with recently formed low-mass companions, brown dwarfs, or giant planets on long-period orbits. However, the origin of the cavity remains controversial, with viscous accretion, photoevaporative winds, dust size evolution, and tidal interactions with stellar or planetary companions remaining as possible explanations (Williams & Cieza 2011). In addition, recent studies in the infrared suggest that some transitional disks may retain a small inner disk, having a gap at intermediate radii instead of a cavity that goes all the way to the star (Espaillat et al. 2012). These disks with a gap instead of a cavity are referred to as pre-transitional disks and are believed to precede in time the transitional disks. Additional studies are needed to clarify the nature of transitional and pre-transitional disks in order to better understand the formation of planetary systems.

Stars with transitional disks were expected to show little or no accretion given the apparent lack of material in the immediate surroundings of the star. However, the presence of accretion (as inferred from ultraviolet/optical excess emission) was found in most stars with transitional disks, albeit at rates about an order of magnitude lower that in classical disks (Najita et al. 2007; Espaillat et al. 2012, 2014). Several mechanisms have been proposed to explain the apparent paradox of simultaneous millimeter transparency and accretion (e.g., Rosenfeld et al. 2014).

Since accretion and ejection in protostars and young stellar objects are correlated, we have started a program to study stars with transitional or pre-transitional disks in the centimeter radio continuum. It is known that collimated outflows from these systems are (partially) ionized and can be detected as weak free–free sources (e.g., Eisloffel et al. 2000). From observations of the [Ne \(\text{II}\)] 12.81 \(\mu\)m line, Pasucci & Sterzik (2009) have shown that photoevaporative winds with velocities of a few km s\(^{-1}\) are present in several transitional disks. The radio free–free is expected to trace a different component, faster and more collimated than a photoevaporative wind.

AB Aur is a Herbig Ae star at a distance of 144 pc (van den Ancker et al. 1997; Oppenheimer et al. 2008), with a mass of 2.4 \(\pm 0.2\) \(M_\odot\), a total luminosity of \(\sim 38\ L_\odot\), and an estimated age of 4 \(\pm 1\) Myr (DeWarf et al. 2003). AB Aur was considered for many years as the prototype of the Herbig Ae star surrounded by a large envelope and a disk. However, recent sensitive observations have modified this picture. Near-IR observations from Subaru by Fukagawa et al. (2004) revealed spiral arms of enigmatic origin in the disk. Using the IRAM array to image the CO(2–1) and \(^{13}\text{CO}(2–1)\) transitions and the continuum emission at 1.3 mm, Piétu et al. (2005) found that the dust disk is truncated at an inner radius of about 70 AU from the central star. Using the Submillimeter Array (SMA), Lin et al. (2006) found molecular spiral arms in the CO(3–2) emission. Hashimoto et al. (2011) has set an upper limit of 5 \(M_\odot\) for a possible companion to AB Aur.
Tang et al. (2012) mapped the CO(2−1) and the 1.3 mm continuum emissions combining data from the Plateau de Bure Interferometer array and the SMA, confirming the results of Piétu et al. (2005). However, these sensitive observations revealed the presence of a CO disk inside the cavity with an inclination angle slightly different from that measured in the CO outer disk. This molecular gas shows a velocity gradient and is consistent with an inner disk whose rotation axis is at a position angle of 142° ± 1°. Rodríguez et al. (2007) obtained high angular resolution, high-sensitivity Very Large Array (VLA) observations at 3.6 cm and confirmed the existence of radio continuum emission associated with the star (Guedel et al. 1989; Skinner et al. 1993). Rodríguez et al. (2007) also detected a new, faint protuberance that extended about 0′′3 to the southeast of AB Aur, at a position angle of 139° ± 12°. Since this protuberance is well aligned with the rotation axis of the inner disk detected in CO, it could well be a one-sided collimated outflow, as observed in other sources (i.e., DG Tau; Rodríguez et al. 2012). The possibility of the radio protuberance tracing a faint radio companion was also discussed by these authors, without reaching a firm conclusion. In this paper we present new, very sensitive radio observations to better understand the nature of the centimeter emission.

2. OBSERVATIONS

The observations were made with the VLA of NRAO centered at a rest frequency of 8.9 GHz (3.3 cm) during 2012 December. At that time the array was in its A configuration. The phase center was at α(2000) = 04h55m45.8s, δ(2000) = +30° 33′ 03″.99. The absolute amplitude calibrator was J0137+3309 and the phase calibrator was J0443+3441.

The digital correlator of the VLA was configured in 16 spectral windows of 128 MHz width divided in 64 channels of spectral resolution. The total bandwidth for the continuum observations was about 2.0 GHz in a dual-polarization mode.

The data were analyzed in the standard manner using the CASA (Common Astronomy Software Applications) package of NRAO using the pipeline provided for VLA observations. Maps were made using natural weighting in order to obtain a slightly better sensitivity. The resulting image rms was 2.9 μJy beam−1 at an angular resolution of 0′′28 × 0′′25 with position angle (P.A.) = +45°1.

In Figure 1 we show the 3.3 cm emission of AB Aur overlaid on an image of the 1.3 mm emission from Tang et al. (2012). The total emission at 3.3 cm is 136 ± 6 μJy and the source is elongated, with deconvolved dimensions of 0′′17 ± 0′′02 ≤ 0′′06 ± 0′′02; P.A. = 161° ± 7°. The major axis of the 3.3 cm emission is approximately parallel to the rotation axis of the high-velocity CO gas studied by Tang et al. (2012) that has P.A. = 142° ± 1°.

To obtain additional information on the radio spectrum of AB Aur, Q band (∼7mm) observations from the VLA archive were analyzed. These observations were taken in the D (observed in three runs during 2010 August 10 and 12 and 2010 September 2) and C (2010 November 19) configurations (VLA project code: AC982). The flux calibrator was 3C147, while the phase calibrator was J0443+3441. The phase center for all the observations was R.A.(J2000) = 04h55m45s.944, decl.(J2000) = +30°33′05″.79. The digital correlator of the JVLA was configured in 16 spectral windows of 128 MHz width divided in 64 channels of spectral resolution. The total bandwidth for the continuum observations was 2 GHz in dual-polarization mode.

Data editing and calibration were performed also using the data reduction package CASA, following the standard high-frequency JVLA procedures. An averaging in time (∼9 s) and in channels (four channels = 8 MHz) was performed in order to reduce the volume of the data.

Cleaned images at 7 mm were made with the task clean of CASA by using the multi-scale multi-frequency deconvolution algorithm described in Rau & Cornwell (2011). By concatenating the data from both configurations (C and D) and using natural weighting, we obtained an rms of 25 μJy beam−1 and a synthesized beam of 0′′90 × 0′′70 with P.A. = −65°5. We detect an unresolved source (Figure 2) centered at the position R.A.(J2000) = 04h55m45.846 ± 0″002, decl.(J2000) = +30°33′04″.04 ± 0″.02. The total flux density at 7 mm is 0.84 ± 0.03 mJy.

3. INTERPRETATION

3.1. The Nature of the Radio Continuum Emission

AB Aur has been detected previously as a centimeter continuum source. Using the VLA, Guedel et al. (1989) detected it at 3.6 cm in 1988 October 7 with a flux density of 146 ± 25 μJy and at 3.6 and 6 cm in 1988 October 27 with flux densities of 112 ± 24 μJy and 119 ± 20 μJy, respectively. These authors noted that the radio spectrum deviates from the simple ν0.8 power law expected for a conical free–free outflow and suggested that the 6 cm emission could have a non-thermal contribution. Skinner et al. (1993) detected AB Aur at 3.6 cm with flux densities of 140 ± 20 μJy and 150 ± 50 μJy in data taken on 1990 February 10, 11, and 13 and in 1991 June 1, respectively.
In addition, AB Aur was detected at 3.6 cm with a flux density of $200 \pm 30 \mu$Jy in 2006 April 28 (Rodríguez et al. 2007). From observations made in 2011 February, April and May, S. A. Dzib et al. (2014, in preparation) report flux densities for AB Aur of $89 \pm 19 \mu$Jy at 6.7 cm $= 4.5$ GHz) and $167 \pm 25 \mu$Jy at 4.0 cm $= 7.5$ GHz). The flux density detected by us at 8.9 GHz (136 $\pm 6 \mu$Jy) is consistent with that detected since 1989 at similar frequencies. This result implies that the centimeter emission of AB Aur is, within noise, steady in time.

The transitional disk of AB Aur has also been detected at millimeter wavelengths, with total flux densities of $350 \pm 20$ mJy and $2200 \pm 100$ mJy at 850 and 450 $\mu$m, respectively (Sandell et al. 2011). Tang et al. (2012) report a total flux density of $110 \pm 1$ mJy at 1.3 mm (230 GHz). These large flux densities are dominated by the transitional disk that is evident in Figure 1. However, Tang et al. (2012) note that within the cavity they detect a compact source with a flux density of $1.3 \pm 0.2$ mJy and suggest that this emission could be due purely to free–free emission from an ionized jet. In Figure 3 we show the continuum spectrum of the emission closely associated with the star. The points at 42.0 GHz and lower frequencies have been least-squares fitted to a power law of the form $(S_\nu/\mu$Jy$) = 12 \pm 5 (\nu/$GHz$)^{1.1 \pm 0.1}$. This spectral index in consistent with the values expected for a free–free jet (Reynolds 1986). The flux density measured at 230 GHz by Tang et al. (2012) falls a factor of $\sim 4$ below the extrapolated flux density from the power law fit. This suggests that the jet has become optically thin at $\sim 70$ GHz.

An interesting alternative possibility to the jet is that of a photoevaporating circumstellar disk (Pascucci et al. 2012). If the central star produces sufficient extreme-ultraviolet (13.6 eV $< h\nu \leq 100$ eV) or X-ray photons, the surface layers of the disk are ionized and produce a slow ($\sim 10$ km s$^{-1}$) photoevaporative wind that can be detected as a weak free–free source (Pascucci et al. 2012; Owen et al. 2013). However, we favor the jet interpretation on two grounds. First, the region of free–free emission in the photoevaporating disk is small ($\sim 10$ AU; Pascucci et al. 2012; Owen et al. 2013) and will appear as unresolved in our data. In contrast, the detected radio source is clearly resolved in one axis. The second argument is that the free–free emission from photoevaporating disks is expected to show a flat spectrum (Pascucci et al. 2012), while the detected source has a spectrum that rises with frequency. The lack of clear radio detections of photoevaporating disks (Galván-Madrid et al. 2014; Pascucci et al. 2014) has led these latter authors to propose that these winds could be largely neutral.

In summary, the radio continuum emission associated with AB Aur can be interpreted as a thermal jet (e.g., Anglada 1996; Eislöffel et al. 2000). Its morphology, orientation with respect to the inner CO disk, spectral index, and lack of significant time variability are all in agreement with this interpretation.

3.2. Comparison with other Jets

Given that AB Aur is associated with a transitional disk, we expect its radio jet to be weaker than those observed in forming stars with classical (full) disks. By a full disk we refer to a disk with no significant discontinuities in its radial dust distribution. In sources with classical disks, the radio luminosity of the radio jet $(S_\nu d^2, \text{with } S_\nu \text{ the flux density at } 8.3 \text{ GHz and } d \text{ the distance})$ is correlated with the bolometric luminosity of the source, $L_{\text{bol}}$, by (Anglada 1995; Anglada et al. 2014)

\begin{equation}
\frac{S_\nu d^2}{\text{mJy kpc}^2} = 0.008 \left(\frac{L_{\text{bol}}}{L_\odot}\right)^{0.6}.
\end{equation}

Since for AB Aur $L_{\text{bol}} = 38 L_\odot$ and $d = 144$ pc, a flux density of $\sim 3$ mJy is expected at 8.3 GHz. In contrast, we detect a flux density of $\sim 0.14$ mJy, a factor of $\sim 20$ below the value expected for a classical disk.

As noted above, accretion is also known to be present in transitional disks, although at rates an order of magnitude
smaller than those present in classical disks. Our results suggest that outflows are also present in systems with transitional disks, but again at significantly lower rates than those observed in classical disks. The correlation given above is most probably valid only for very young stars, where most of the luminosity comes from accretion. In an object like AB Aur most of the luminosity comes from the star.

It is relevant to compare the accretion and outflow rates in AB Aur. From near-infrared hydrogen recombination lines, its accretion rate is estimated to be $\dot{M}_{\text{acc}} \sim 1.4 \times 10^{-7} M_\odot \text{ yr}^{-1}$ (Garcia Lopez et al. 2006; Salyk et al. 2013). The radio luminosity is also correlated with $\dot{P}_{\text{out}}$, the momentum rate of the outflow, by (Anglada 1995; Anglada et al. 2014)

$$\left( \frac{S_\nu d^2}{\text{mJy km s}^{-1}} \right) = 190 \left( \frac{\dot{P}_{\text{out}}}{M_\odot \text{ yr}^{-1} \text{ km s}^{-1}} \right)^{0.9}. \tag{2}$$

Thus, from the observed radio luminosity, we expect $\dot{P}_{\text{out}} \simeq 5.0 \times 10^{-6} M_\odot \text{ yr}^{-1} \text{ km s}^{-1}$. Adopting a jet terminal velocity of $300 \text{ km s}^{-1}$, we estimate a mass loss rate of $\dot{M}_{\text{out}} \sim 1.7 \times 10^{-8} M_\odot \text{ yr}^{-1}$. The mass loss rate is then about a tenth of the accretion rate, the approximate ratio deduced for full disks (Cabrit 2007). It is then interesting that although stars with transitional disks present lower mass accretion and mass loss rates, the ratio $\dot{M}_{\text{out}}/\dot{M}_{\text{acc}}$ is ~0.1, as observed in less evolved objects.

We thank Y.-W. Tang for providing us with her 1.3 mm image of AB Aur. L.F.R., L.A.Z., and L.L. acknowledge the financial support of CONACyT, México and DGAPA, UNAM. G.A. and E.M. acknowledge support from MICINN (Spain) AYA2011-30228-C03-01 grant (co-funded with FEDER funds).

REFERENCES

Andrews, S. M., Wilner, D. J., Espaillat, C., et al. 2011, ApJ, 732, 42

Anglada, G. 1995, RMxAA, 1, 67

Anglada, G. 1996, in ASP Conf. Ser. 93, Radio Emission from the Stars and the Sun, ed. A. R. Taylor & J. M. Paredes (San Francisco, CA: ASP), 3

Anglada, G., Rodríguez, L. F., & Carrasco-González, C. 2014, in Advancing Astrophysics with the Square Kilometer Array, Proceedings of Science, in press

Brown, J. M., Blake, G. A., Qi, C., et al. 2009, ApJ, 704, 496

Cabrit, S. 2007, LNP, 723, 21

Calvet, N., D’Alessio, P., Hartmann, L., et al. 2002, ApJ, 568, 1008

D’Alessio, P., Hartmann, L., Calvet, N., et al. 2005, ApJ, 621, 461

DeWarf, L. E., Sepinsky, J. F., Guinan, E. F., Ribas, I., & Nadalin, I. 2003, ApJ, 590, 357

Eislöffel, J., Mundt, R., Ray, T. P., & Rodríguez, L. F. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson, AZ: Univ. Arizona Press), 815

Espaillat, C., Ingleby, L., Hernández, J., et al. 2012, ApJ, 747, 103

Espaillat, C., Muzerolle, J., Najita, J., et al. 2014, arXiv:1402.7103

Fukagawa, M., Hayashi, M., Tamura, M., et al. 2004, ApJL, 605, L53

Galván-Madrid, R., Liu, H. B., Manara, C. F., et al. 2014, A&A, submitted

Garcia Lopez, R., Natta, A., Testi, L., & Habart, E. 2006, A&A, 459, 837

Geers, V. C., Pontoppidan, K. M., van Dishoeck, E. F., et al. 2007, A&A, 469, L35

Guedel, M., Benz, A. O., Catala, C., & Praderie, F. 1989, A&A, 217, L9

Hashimoto, J., Tamura, M., Muto, T., et al. 2011, ApJL, 729, L17

Kim, K. H., Watson, D. M., Manoj, P., et al. 2013, ApJ, 769, 149

Lin, S.-Y., Ohashi, N., Lim, J., et al. 2006, ApJ, 645, 1297

Najita, J. R., Strom, S. E., & Muzerolle, J. 2007, MNRAS, 378, 369

Oppenheimer, B. R., Brenner, D., Hinkley, S., et al. 2008, ApJ, 679, 1574

Owen, J. E., Scaife, A. M. M., & Ercolano, B. 2013, MNRAS, 434, 3378

Pascucci, I., Gorti, U., & Hollenbach, D. 2012, ApJL, 751, L42

Pascucci, I., Ricci, L., Gorti, U., et al. 2014, arXiv:1407.1574

Pascucci, I., & Sterzik, M. 2009, ApJL, 702, 724

Pérez, L. M., Pontoppidan, K. M., van Dishoeck, E. F., & Chandler, C. J. 2014, ApJL, 783, L13

Piétu, V., Guilloteau, S., & Dutrey, A. 2005, A&A, 443, 945

Rau, U., & Cornwell, T. J. 2011, A&A, 532, A71

Reynolds, S. P. 1986, ApJ, 304, 713

Rodríguez, L. F., González, R. F., Raga, A. C., et al. 2012, A&A, 537, A123

Rodríguez, L. F., Zapata, L., & Ho, P. T. P. 2007, RMxAA, 43, 149

Rosenfeld, K. A., Chiang, E., & Andrews, S. M. 2014, ApJ, 782, 62

Salyk, C., Herczeg, G. J., Brown, J. M., et al. 2013, ApJ, 769, 21

Sandell, G., Weintraub, D. A., & Hamidouche, M. 2011, ApJ, 727, 26

Skinner, S. L., Brown, A., & Stewart, R. T. 1993, ApJS, 87, 217

Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451

Tang, Y.-W., Guilloteau, S., Piétu, V., et al. 2012, A&A, 547, A84

van den Ancker, M. E., The, P. S., Tjin A Djie, H. R. E., et al. 1997, A&A, 324, L33

van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2013, Sci, 340, 1199

van Leeuwen, F. 2007, A&A, 474, 109

Williams, J. P., & Cieza, L. A. 2011, ARA&A, 49, 67