Revista Mexicana de Astronomía y Astrofísica, **60**, 355–359 (2024)

https://doi.org/10.22201/ia.01851101p.2024.60.02.12

THE RADIO CONTINUUM SOURCE PROJECTED NEAR HR 8799

L. F. Rodríguez[1,2] and L. A. Zapata[1]

Received February 17 2024; accepted July 3 2024

ABSTRACT

HR 8799 is an A5/F0 V star where exoplanets were first directly imaged. Four exoplanets were found within $\simeq 2\rlap{.}''0$ from the star. Here we report the VLA detection of a faint (19.1±2.7 μJy) radio continuum (3.0 GHz) source projected at $\simeq 2\rlap{.}''2$ from the star. The *a priori* probability of finding a background source with this flux density within a radius of $2\rlap{.}''2$ is only 0.0046. However, the astrometry made with the VLA and ALMA images, separated by 5.5 years, indicates no significant proper motions and rules out the association of the radio source with the HR 8799 system and suggests it is a background millimeter galaxy with dust emission in the millimeter and partially thick synchrotron emission in the centimeter.

RESUMEN

HR 8799 es una estrella A5/F0 V en la cual se detectaron por primera vez exoplanetas con la técnica de imágenes directas. Se encontraron cuatro exoplanetas dentro de $\simeq 2\rlap{.}''0$ de la estrella. Aquí reportamos la detección con el VLA de una fuente débil de radio continuo (19.1±2.7 μJy) a una frecuencia de 3.0 GHz proyectada a $\simeq 2\rlap{.}''2$ de la estrella. La probabilidad *a priori* de encontrar una fuente de fondo con esta densidad de flujo dentro de un radio de $2\rlap{.}''2$ es sólo 0.0046. Sin embargo, la astrometría realizada con las imágenes del VLA y ALMA, separadas por 5.5 años, indica que no hay movimientos propios significativos, descarta la asociación de la fuente de radio con el sistema HR 8799 y sugiere que se trata de una galaxia milimétrica de fondo con emisión de polvo en el milimétrico y emisión sincrotrón parcialmente ópticamente gruesa en el centimétrico.

Key Words: astrometry — proper motions — radio continuum: general — stars: individual: HR 8799

1. INTRODUCTION

More than 100 exoplanets have been discovered with the technique of direct imaging, as listed in the NASA Exoplanet Archive (Akeson et al. 2013). HR 8799 is the star where exoplanets were first directly imaged. Four exoplanets were found within ≈80 au (≈ 2″ at the distance of 40.85 pc) in the plane of the sky from the star (Marois et al. 2008; 2010). The observed proper motions of the exoplanets around the star confirmed the association (Close & Males 2010). In addition to the four exoplanets, HR 8799 exhibits a debris disk (Booth et al. 2016; Wilner et al. 2018), extending from $\simeq$ 2″ ($\simeq$80 au) to $\simeq$ 7″ ($\simeq$280 au) in radius, with a clear central cavity, and detectable in the sub-millimeter (Faramaz et al. 2021). In addition, these authors report the presence of an 880 μm point source associated with the star.

In this paper we present sensitive VLA observations of the HR 8799 region obtained with the purpose of searching for emission from the star or from one of its four exoplanets. In § 2 we discuss the observations, while in § 3 we interpret the data. Finally, our conclusions are presented in § 4.

2. OBSERVATIONS

2.1. *VLA*

The data of project 12B-188 were obtained from the archives of the Karl G. Jansky Very Large Array (VLA) of NRAO[3]. These observations were made with the highest angular resolution **A** configuration

[1]Instituto de Radioastronomía y Astrofísica, UNAM, México.

[2]Mesoamerican Center for Theoretical Physics, UNACH, México.

[3]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

TABLE 1

PARAMETERS OF THE VLA AND ALMA OBSERVATIONS OF THE HR 8799 REGION

Project	Mean Epoch	Telescope	Frequency/ Bandwidth	Deconvolved Dimensions	Total Flux Density	Position[a] RA(J2000)[b]	DEC(J2000)[c]
12B-188	2012.88	VLA	3/2 GHz	$0''.5\pm0''.2\times0''.2\pm0''.2;+71^\circ\pm35^\circ$	19.1±2.7 μJy	$28^s.763\pm0^s.003$	$04''.71\pm0''.03$
2016.1.00907.S	2018.38	ALMA	340/8 GHz	$0''.5\pm0''.1\times0''.5\pm0''.1;+160^\circ\pm91^\circ$	207±10 μJy	$28^s.764\pm0^s.003$	$04''.68\pm0''.05$

[a]For the epoch of the observations.
[b]23^h07^m.
[c]$+21^\circ08'$.

during six epochs between 2012 October 31 and 2012 November 26. The observations were made in the S-band continuum (2-4 GHz), with 16 spectral windows of 128 MHz each. These spectral windows were divided into 64 channels of 2 MHz individual width. The amplitude calibrator was J0137+3309 (3C48) and the gain calibrator was J2254+2445. The data were calibrated in the standard manner using the version 5.6.2-3 of the CASA (Common Astronomy Software Applications; McMullin et al. 2007) package of NRAO and the pipeline provided for VLA[4] observations. The data of the six epochs were concatenated in a single file to increase the signal-to-noise ratio. The images were made using a robust weighting of 2 (Briggs 1995), to optimize the sensitivity at the expense of losing some angular resolution.

2.2. *ALMA*

The sub-millimeter continuum data (at 340 GHz) were obtained from the ALMA data archive. The project was conducted under the program 2016.1.00907.S (PI: V. Faramaz). For this study, we only used the 12 m array observations carried out from 2018 May 13 to June 1. The data were taken using baselines ranging from 15 to 314 m (18 to 392 kλ). The ALMA digital correlator was configured with four spectral windows (SPWs), each one 2 GHz wide. Three of these SPWs were used for the continuum, and one for the detection of the CO(3−2) molecular line at a rest frequency of 345.79598990 GHz. Bright quasars J2148+0657, J2253+1608, and J2253+1608 were used as flux, bandpass, and gain phase calibrators. The total time on-source was 4.5 hrs. The raw data were calibrated, and then imaged using the Common Astronomy Software Applications (CASA) version 5.1.1. The digital correlator was set up with three spectral windows with a bandwidth of 2 GHz (divided into 128 channels resulting in a channel width of 15.625 MHz) and one spectral window with a bandwidth of 1.875 GHz (divided into 3840 channels resulting in a channel width of 488.281 kHz). The CO(3−2) line was the only spectral line excluded during the process of the continuum construction. We obtained an image rms noise for the continuum at 0.8 mm of 10 μJy beam^{-1} at an angular resolution of $0''.88 \times 0''.76$; 14°. This angular resolution is very similar to that obtained in the VLA image (see caption of Figure 1). We used a robust parameter equal to 0.5 in the TCLEAN task, an adequate compromise between angular resolution and sensitivity. The parameters of the sub-millimeter source detected are given in Table 1. The ALMA observations were not configured to detect any polarized emission. For both the VLA and the ALMA observations we fitted the data in the image plane with the task IMFIT of CASA. The results of such fittings are given in Table 1. Our derived value for ALMA, 207±10 μJy is lower than the value of 316±20 μJy obtained by Faramaz et al. (2021). This difference is probably due to the fact that Faramaz et al. (2021) included in their analysis data from the Atacama Compact Array, recovering more extended flux.

[4]`https://science.nrao.edu/facilities/vla/data-processing/pipeline`.

3. INTERPRETATION

3.1. *VLA data*

The final image (Figure 1) reveals the presence of a 3.0 GHz source about $2''.2$ to the north of HR 8799. This radio source does not coincide in position with the star or with any of its exoplanets and appears to be located at the inner edge of the debris disk of HR 8799. In Figure 1 we show the radio continuum source as well as the positions of HR 8799 and its four exoplanets for epoch 2012.88, corrected for the proper motions of the star from Gaia DR3 (Gaia collaboration et al. 2023) and an interpolation of the orbital motions of the exoplanets with respect to the star taken from Konopacky et al. (2016). In Figure 1 we also show the approximate position of the inner radius of the debris disk. The best-fit model for this parameter given by Faramaz et al. (2021) is 135±4 au, that at the distance of 40.85 pc derived from the Gaia DR3 parallax equals 3.3±0.1 arcsec.

The parameters of the radio source are given in Table 1. No circular polarization was detected at an

DOI: https://doi.org/10.22201/ia.01851101p.2024.60.02.12

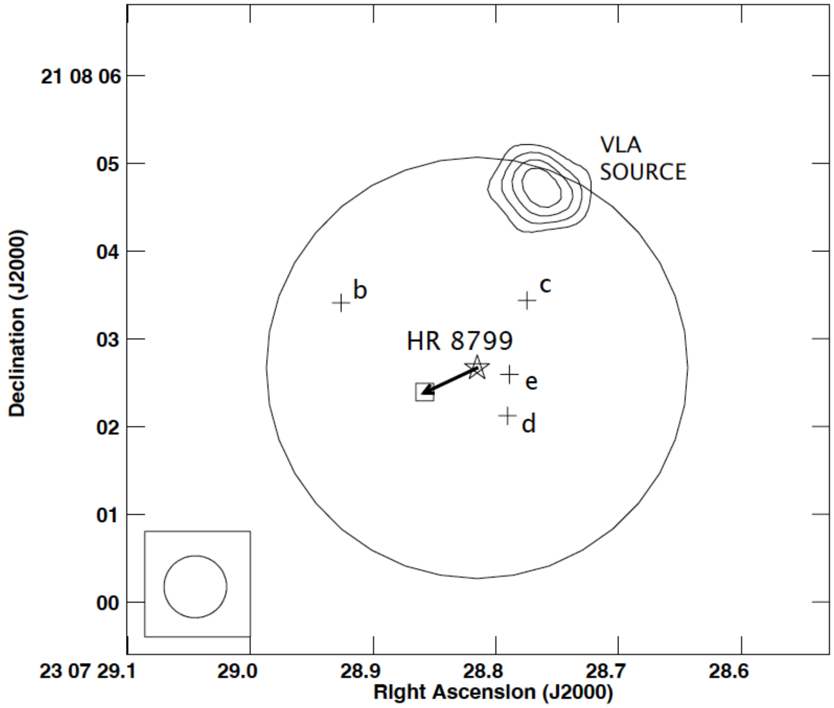

Fig. 1. Objects in the vicinity of HR 8799. The contours show the Very Large Array source observed at 3.0 GHz for epoch 2012.88. Contours are -4, 4, 6, 8 and 10 times 1.28 μJy beam^{-1}, the rms noise in this region of the image. The synthesized beam ($0\farcs71 \times 0\farcs71; -85\fdg6$) is shown in the bottom left corner of the image. The positions of HR 8799 (star) and its four exoplanets b, c, d, and e (crosses) have been corrected for proper motions and the orbital motions of the exoplanets to the epoch of the VLA observations (2012.88). The large circle marks the inner edge of the debris disk and shows that all four exoplanets as weLl as the VLA source fall inside this inner edge. The arrow gives the proper motion of HR 8799 between the epoch of the VLA observations (star) and that of the ALMA observations (2018.38), with the position of HR 8799 for this epoch indicated with a square.

absolute upper limit of 19%. What is the *a priori* probability of finding a 3.0 GHz source with a flux density of 19.1 μJy in a circle with radius of $2\farcs2$? To estimate this probability we have used the 3.0 GHz source catalog of Smolčić et al. (2017) to produce a plot of the expected number of background sources as a function of flux density (Figure 2). From this figure we find that the expected number of sources with a flux density equal or larger than 19.1 μJy is 1.1 per square arcmin. Since a circle with radius of $2\farcs2$ has a solid angle of 0.0042 square arcmin, the *a priori* probability is 0.0046, or 1 in 215. This probability is small, but not stringently improbable.

Another characteristic that may help understand the nature of the radio source is its spectral index. Dividing the data in two windows of 1 GHz wide each centered at 2.5 and 3.5 GHz, we obtain flux densities of 16.5±4.1 and 25.3±2.9 μJy, respectively. These flux densities give a spectral index of $\alpha = 1.3 \pm 0.9$ ($S_\nu \propto \nu^\alpha$). The uncertainty is large but the value certainly favors a positive spectral index. This is somewhat unusual for 3.0 GHz background sources since only $\simeq$11% of them have spectral indices $\geq$0.4 (Smolčić et al. 2017), the 1-σ lower limit of our estimate. Finally, we searched for time variability determining the flux density of the source for each of the individual six epochs. We found that all individual six flux densities coincided at the 1-2σ level with the average value given in Table 1, suggesting no variability in a timescale of days to one month.

3.2. *ALMA Data*

In the same way that at 3.0 GHz, we can ask how probable it is that a background source with 0.49 mJy at 338 GHz falls inside the circle with a radius of $2\farcs2$ centered on HR 8799. From the results of Zavala et al. (2017) we estimate that the number of background sources with a flux density of 0.49 mJy or higher at 850 μm is about 4.9 per square arcmin. Then, the *a priori* probability that such a source falls inside the circle with a solid angle of 0.0042 square arcmin is 0.021. Considering that a large number of

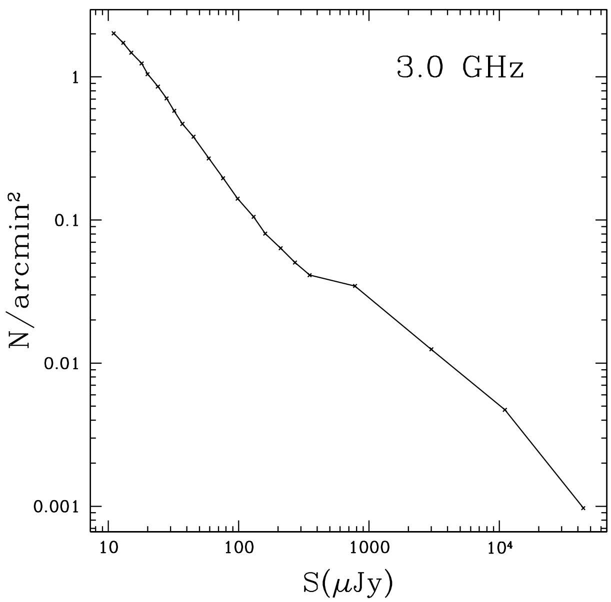

Fig. 2. Expected number of 3.0 GHz sources per square arcmin as function of the flux density lower limit. Derived from Smolčić et al. (2017).

protoplanetary disks is known, this apparent association is not unexpected. Just in Orion, several hundred protoplanetary disks have been detected (van Terwisga et al. 2022). As in the case of the VLA data, we searched for time variability determining the flux density of the source for each of the individual six epochs. We found that all six individual flux densities coincided at the 1-2σ level with the average value given in Table 1, suggesting no variability in a timescale of days to one month.

3.3. *Comparison Between the VLA and the ALMA Data*

Our first conclusion is that despite the low probability of finding a centimeter source so close to HR 8799, the coincidence of positions between the VLA and ALMA data (separated by 5.5 years) rules out the association of the radio source with the HR 8799 system. The two positions coincide within $\leq 0''.03$. HR 8799 has large proper motions, of order $0''.1$ per year ($\mu_\alpha \cos\delta = 108.284 \pm 0.056$ mas yr^{-1}; $\mu_\delta = -50.040 \pm 0.059$ mas yr^{-1}; Gaia collaboration et al. 2023). In the time interval between the two data sets, we expect a total displacement of $\simeq 0''.6$, twenty times larger than our upper limit. This rules out a possible true association between the radio source and the HR 8799 system.

The deconvolved dimensions of the VLA and ALMA sources are consistent within the noise. The spectral index between the 3.0 and 340.0 GHz flux densities is 0.69±0.03. This spectral index and the lack of a proper motion suggest that the radio source is a background millimeter galaxy.

We also note that the data points of Faramaz et al. (2021) have flux densities of 316±20 and 58±18 μJy, at 340 and 230 GHz, respectively. These two points give a spectral index of 4.0±0.9. As noted by Faramaz et al. (2021), this value is too steep to be consistent with the typical millimeter spectral index expected from debris disks (2.5±0.4; MacGregor et al. 2016) and is more consistent with typical values expected for extragalactic dust emission (3.6±0.4; Casey 2012). This source is thus likely to be a background millimeter galaxy. Our 3 GHz flux density (19.1±2.7 μJy) far exceeds the extrapolation of the mm fit to 3 GHz, and at this frequency has a spectral index of 1.3±0.9, suggesting this emission is partially thick synchrotron emission from the galaxy. Recent reviews on protoplanetary disks and debris disks are given by Andrews (2020) and Hughes et al. (2018), respectively.

3.4. *The Arp Effect*

These unlikely associations between sources in the plane of the sky can be called the Arp Effect. Alton Arp (1927-2013) was a distinguished astronomer that studied interacting and apparently interacting galaxies. In some cases, he found that two apparently interacting galaxies close in the sky had different redshifts, leading him to question the cosmological interpretation of redshifts. Several of these apparently interacting sources are described in his Atlas of Peculiar Galaxies (Arp 1966). An example of this type of sources is Stephan's Quintet, that more properly should be called Stephan's Quartet because one of the galaxies is much closer to us than the other four. Arp's Effect can be summarized as follows: if you study a sufficiently large number of sources, you will find some with unlikely apparent associations. Nevertheless, the topic deserves more research.

4. CONCLUSIONS

We analyzed VLA observations of the A5/F0 V star HR 8799, detecting a source at $2''.2$ to the north of HR 8799. The *a priori* probability of finding such a source is 0.0042. Despite this low probability, which suggests a true association, the lack of proper motions, obtained by comparing the VLA data with ALMA data taken 5.5 years after, favors the radio source being a background millimeter galaxy unrelated to the HR 8799 system.

As more protoplanetary and debris disks are studied, other apparent associations are expected to emerge. Another case is HD 95086, where a millimeter source was found projected on its debris disk (Zapata et al. 2018). In this case the lack of a proper motion also favors the source being a background millimeter galaxy. Another example is the source dubbed the "Great Dust Cloud" (Gáspár et al. 2023) apparently associated with Fomalhaut, that has also been interpreted as a background millimeter galaxy (Kennedy et al. 2023).

This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. This research has made use of data obtained from or tools provided by the portal exoplanet.eu of The Extrasolar Planets Encyclopaedia. This work also made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. L.A.Z. acknowledges financial support from CONACyT-280775 and UNAM-PAPIIT IN110618, and IN112323 grants, México. L.F.R. acknowledges the financial support of DGAPA (UNAM) IN105617, IN101418, IN110618 and IN112417 and CONACyT 238631 and 280775-CF Grant 263356.

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Luis F. Rodríguez and Luis A. Zapata: Instituto de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Apartado Postal 3–72, 58090 Morelia, Michoacán, México (l.rodriguez@irya.unam.mx).

Luis F. Rodríguez: Mesoamerican Center for Theoretical Physics, UNACH, México.

DOI: https://doi.org/10.22201/ia.01851101p.2024.60.02.12