Revista Mexicana de Astronomía y Astrofísica, **48**, 243–249 (2012)

RADIO AND OPTICAL OBSERVATIONS OF DG TAU B

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Received 2012 May 7; accepted 2012 June 25

RESUMEN

DG Tau B es un objeto estelar joven de Clase I que produce el chorro bipolar asimétrico HH 159. En longitudes de onda visibles está oscurecido por material circunestelar ópticamente grueso. Usando observaciones del VLA y el JVLA determinamos por primera vez los movimientos propios de esta fuente y los encontramos consistentes, dentro del error, con los de la estrella cercana DG Tau. También discutimos un evento de eyección que es evidente en los datos del VLA de 1994. Al igual que los flujos óptico y molecular, esta eyección observada en el radiocontinuo es marcadamente asimétrica y se detectó sólo hacia el noroeste de la estrella. Proponemos que este nudo, que ya no es detectable en el radio, podría ser observado en futuras imágenes ópticas de DG Tau B. Las posiciones de la fuente VLA y de un objeto infrarrojo cercano no son coincidentes espacialmente y sugerimos que es la fuente VLA la que traza al objeto excitador, mientras que la fuente infrarroja podría ser un lóbulo de reflexión.

ABSTRACT

DG Tau B is a Class I young stellar source that drives the asymmetric HH 159 bipolar jet. At optical wavelengths it is obscured by circumstellar optically-thick material. Using VLA and JVLA observations, we determine for the first time the proper motions of this source and find them to be consistent, within error, with those of the nearby young star DG Tau. We also discuss an ejection event that is evident in the 1994 VLA data. As the optical and molecular outflows, this ejection traced in the radio continuum is markedly asymmetric and was detected only to the NW of the star. We propose that this knot, no longer detectable in the radio, could be observed in future optical images of DG Tau B. The positions of the VLA source and of a nearby infrared object are not coincident and we suggest that the VLA source traces the exciting object, while the infrared source could be a reflection lobe.

Key Words: ISM: jets and outflows — radio continuum: stars — stars: individual (DG Tau B)

1. INTRODUCTION

DG Tau B is a young stellar object that has been classified as a Class I source based on its spectral energy distribution (Watson et al. 2004; Luhman et al. 2010). Its luminosity is estimated to be 0.88 $L_\odot$ (Jones & Cohen 1986). DG Tau B is located in the sky approximately in between the L1495 region and the star HP Tau. There are accurate distance determinations from very long baseline interferometry geometric parallax to both the L1495 region (131.5 pc; Torres et al. 2007, 2012) and HP Tau (161 pc; Torres 2009). Here we adopt for DG Tau B a distance of 150 pc, intermediate to those of L1495 and HP Tau. At optical wavelengths it is obscured by circumstellar optically thick material detected in absorption through broadband imaging with the *Hub-*

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ble Space telescope (Stapelfeldt et al. 1997). It drives the very asymmetric bipolar jet HH 159, first detected by Mundt & Fried (1983). Millimeter ^{13}CO observations (Padgett et al. 1999) indicate that the obscuring material is part of a circumstellar disk of elongated morphology and aligned perpendicular to the axis of HH 159.

While several jets from young stars exhibit considerable symmetry (e.g., HH 212; Correia et al. 2009), the HH 159 jet has always been remarkable for its asymmetry (Podio et al. 2011). The red optical lobe consists of a chain of bright knots extending to $\sim 55''$ to the NW of the source, while the blue optical lobe is fainter and less collimated, and is detected only up to $\sim 10''$ to the SE of the source (Mundt, Ray, & Raga 1991; Eislöffel & Mundt 1998). McGroarty & Ray (2004) proposed that the Herbig-Haro objects 836 and 837, located several arcmin to the SE of DG Tau B, could be tracing ejecta from this star that took place $\sim 10^4$ years ago. A large molecular outflow spatially coincident with the redshifted optical jet has been detected in the CO lines by Mitchell et al. (1994) and Mitchell, Sargent, & Mannings (1997). These authors find that the CO outflow is similar to the optical outflow: the CO redshifted emission extends at least 6000 AU ($40''$ at the distance of 150 pc) to the NW of the star, while the blueshifted CO emission is confined to a compact region, which is less than 500 AU ($\sim 3''$) in radius. Mitchell et al. (1997) suggest that a molecular clump or core surrounds DG Tau B.

DG Tau B was first detected in the radio continuum by Rodríguez, Anglada, & Raga (1995), who found a sub-arcsecond elongated source (with deconvolved angular dimensions of $0.''38 \pm 0.''02 \times 0.''22 \pm 0.''02$), with its major axis aligned along a position angle of $298^\circ \pm 5^\circ$, coincident within a few degrees with the position angle of the axis of the optical and molecular outflows ($\sim 294^\circ$). These authors proposed that the radio emission was tracing the base of the collimated jet responsible for the optical and molecular outflows. Using VLA observations and data from the literature (Mitchell et al. 1997; Looney, Mundy, & Welch 2000), the study by Rodmann et al. (2006) found a spectral index of $\alpha = 0.3$ ($S_\nu \propto \nu^\alpha$) in the 3.6 cm to 1.3 cm range, and of $\alpha = 2.9$ in the 7 mm to 2.6 mm range. The spectral index in the centimeter range is consistent with a thermal (free-free) jet, while that in the millimeter range indicates optically-thin emission from dust.

In this paper we use archive data from the Very Large Array (VLA) and the Jansky Very Large Array (JVLA) of the NRAO[7] to study the flux density, morphology, and proper motions of the radio source associated with DG Tau B in the period since its detection in 1994 VLA data (Rodríguez et al. 1995). We also use optical images to search for newly ejected knots and to discuss the identification of the exciting source of the system.

TABLE 1

FLUX DENSITIES OF DG TAU B AT 3.6 CM

Epoch	Flux Density (mJy)	VLA/JVLA Configuration	VLA/JVLA Project
1994 Apr 16	0.30±0.05[a]	A	AR277
1994 Jul 08	0.29±0.05	B	AW386
1996 Dec 24	0.32±0.04	A	AR277
1997 Dec 15	0.44±0.08	D	AW472
1999 Nov 18	0.32±0.05	B	AW522
2003 Mar 21	0.36±0.04	D	AM756
2009 Aug 13	0.34±0.02	C	AR694
2011 Apr 01[b]	0.29±0.01[c]	B	BL175

[a]This flux density comes from the component associated with the star. The ejected knot to the NW has a flux density of 0.26 ± 0.05 mJy.
[b]Mean epoch of the three epochs observed with the JVLA: 2011 February 27, 2011 March 20, and 2011 May 05.
[c]Flux density at 4.0 cm from the concatenated data of the three epochs.

2. RADIO OBSERVATIONS

The archive epochs used are listed in Table 1. All epochs, except the last one, were obtained with the VLA at 3.6 cm using a 100 MHz effective bandwidth, and were edited and calibrated using the software package Astronomical Image Processing System (AIPS) of NRAO. The last epoch is the average of three observations made at 4.0 cm with the JVLA (Jansky Very Large Array) in 2011 February 27, March 20, and May 5. These observations were made with an effective bandwidth of 1 GHz and are part of the Gould's Belt Distance Survey (Loinard et al. 2011). They were edited and calibrated with the software package Common Astronomy Software Applications (CASA). The full set of observations covers about 17 years.

2.1. *Flux density as a function of time*

In Table 1 we show the flux densities of DG Tau B as a function of time. The flux density appears to

[7]The National Radio Astronomy Observatory is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.

be approximately constant, with a weighted mean and weighted standard deviation given by 0.305 ± 0.026 mJy. To test statistically the possibility of time variation, we did a χ^2 fitting to the 8 data points assuming they are modeled by a constant with a flux density of 0.305 mJy. We obtain a value of $\chi^2 = 10.4$, which is somewhat high, but still consistent with the range expected for a good fit, which is given by $\nu \pm \sqrt{2\nu}$ (Press et al. 1992), with ν being the number of degrees of freedom. In our case $\nu = 7$ and the range of χ^2 for a good fit is 7.0 ± 3.7. We then conclude that DG Tau B does not show significant flux density variations over the time interval covered by the observations.

2.2. *Proper motions*

There are several limitations to undertake the astrometry of a radio source from VLA and JVLA archive observations. The observations have to be made with good signal to noise ratios and the best angular resolution possible. In addition, the same phase calibrator should have been used in the observations. With these limitations, we found only five epochs of data (1994 April 16, 1994 July 8, 1994 December 24, 2009 August 13, and 2011 April 1), four with the VLA and the last one with the JVLA that could be used. All observations used J0403+260 as phase calibrator. The position of DG Tau B as a function of time is shown in Figure 1. For the first epoch we assumed that the position of the star was that of the SE component (see Figure 2 and discussion below). The proper motions derived from these positions are

$$\mu_\alpha \cos\delta \;=\; +3.8 \pm 1.9 \text{ mas yr}^{-1},$$
$$\mu_\delta \;=\; -20.6 \pm 3.3 \text{ mas yr}^{-1}.$$

The correlation coefficients for these fits are 0.67 for the right ascension and −0.95 for the declination. These proper motions are consistent within 2σ with those reported by Rodríguez et al. (2012) for the nearby young star DG Tau (located $\sim 54''$ to the NE of DG Tau B). This result confirms that, as expected, DG Tau and DG Tau B share very similar proper motions since they are part of the same star-forming region. There are no proper motions for DG Tau B from other wavelengths since it is a heavily obscured object.

2.3. *Morphology*

The image of Rodríguez et al. (1995) clearly shows an elongated source. However, the stellar position of DG Tau B was poorly known then and it was not possible to accurately position the star with

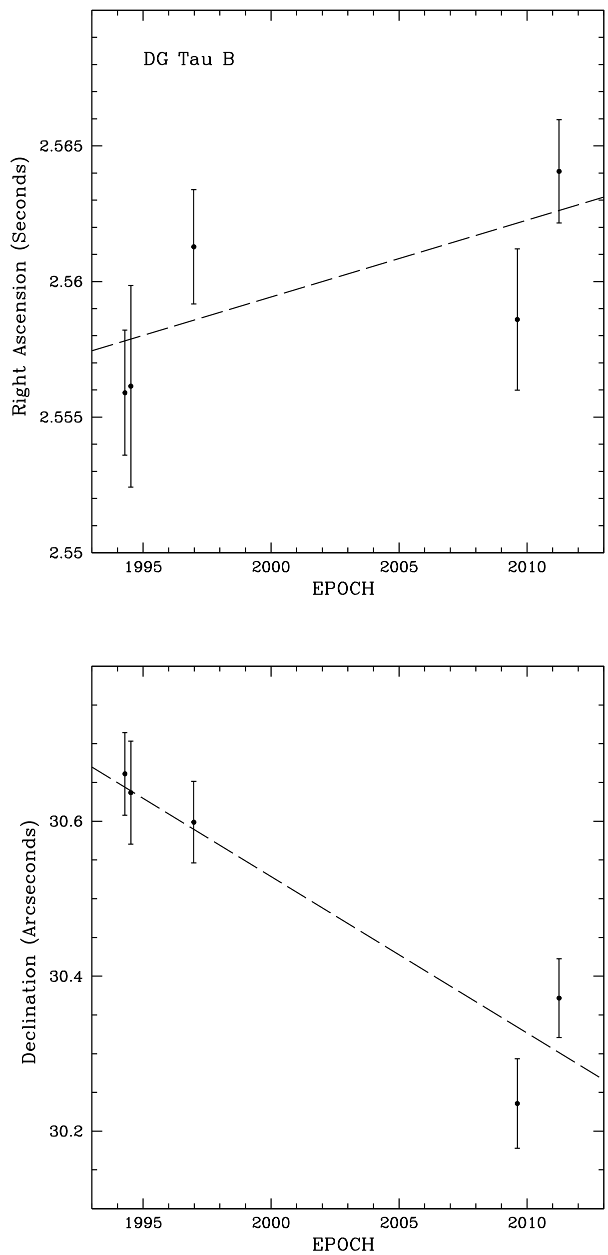

Fig. 1. Position of the radio emission of DG Tau B as a function of time from VLA and JVLA data. The right ascension (top) is given with respect to $04^h\ 27^m$ and the declination (bottom) with respect to $+26^\circ\ 05'$. The dashed lines are least-squares fits to the data that give the proper motions discussed in the text.

respect to the radio emission. Our reanalysis of the data confirms the elongated structure and suggests that we are actually observing a double source (see Figure 2). It is possible to fit this structure with two sources separated by $0''.21 \pm 0''.04$ and with 3.6 cm flux densities of 0.30 ± 0.05 mJy and 0.22 ± 0.05 mJy

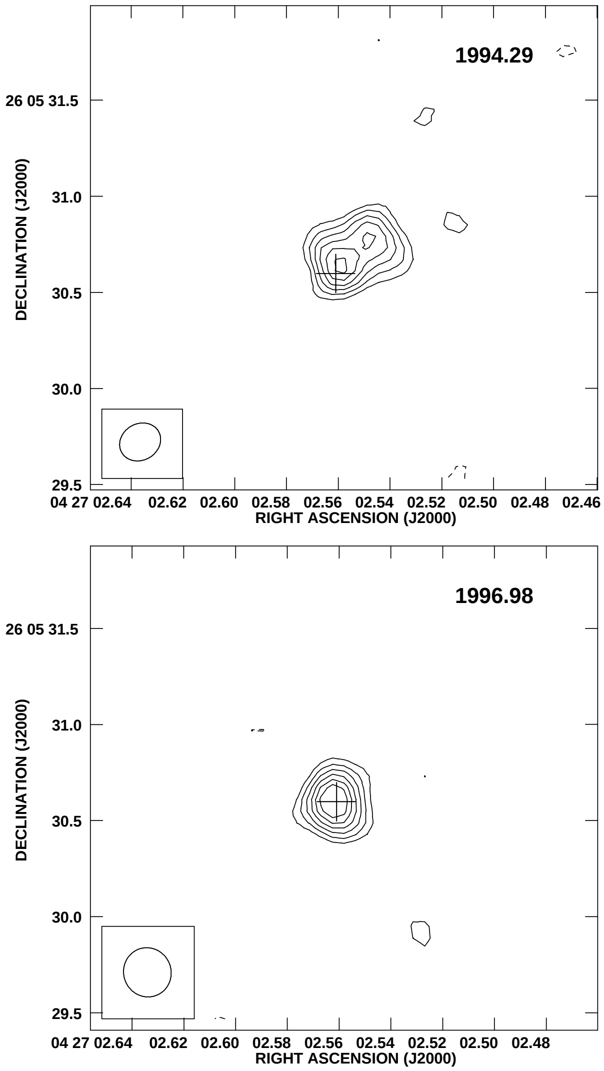

Fig. 2. VLA contour images of the 3.6-cm continuum emission toward DG Tau B. (Top) Image for 1994 April 16. Contours are −3, 3, 4, 5, 6, 7, and 8 times 0.015 mJy beam^{-1}, the rms noise of the image. The synthesized beam, shown in the bottom left corner, has half power full width dimensions of $0\farcs22 \times 0\farcs19$, with the major axis at a position angle of −60°. (Bottom) Image for 1996 December 24. Contours are −3, 3, 4, 5, 6, 7, and 8 times 0.015 mJy beam^{-1}, the rms noise of the image. The synthesized beam, shown in the bottom left corner, has half power full width dimensions of $0\farcs26 \times 0\farcs25$, with the major axis at a position angle of +21°. The cross marks the radio position of DG Tau B in this second epoch, $\alpha(2000) = 04^h\ 27^m\ 02\fs561; \delta(2000) = +26^\circ\ 05'\ 30\farcs60$.

for the SE and NW components, respectively. We assumed that the SE component is the one associated with the star. We believe that this assumption is correct since this position is consistent with the rest of the astrometry, with the other four epochs not showing evidence for an additional component. We conclude that the NW component seen in 1994 (see top panel of Figure 2) is probably an ejecta that took place somewhere in the past. The 1996 December 24 image (see bottom panel of Figure 2), of angular resolution and sensitivity very similar to those of the 1994 April 16 image, does not show the ejecta at a level ≈4 times lower than that present in 1994.

The radio ejecta from young stellar objects are known to decrease in flux density with time and eventually become undetectable in timescales of years (e.g., Martí, Rodríguez, & Reipurth 1998). We thus find the non-detection of the knot in the 1996 data consistent with what is known of radio knots from young stellar objects. However, we now address the following question: is the radio knot observed in 1994 evident in more recent optical images of the HH 159 jet? The optical observations are much more sensitive for the detection of knots than the radio ones. In the nearby young star DG Tau, Rodríguez et al. (2012) find that the radio knots are, within positional error, coincident with optical knots.

From the observations made between 1986 and 1990, Eislöffel & Mundt (1998) determine an average proper motion of 0.12 ± 0.03 arcsec yr^{-1} (87 ± 22 km s^{-1}) away from the star for the five inner optical knots of the NW lobe (knots A1, A3, A2, B1, and B2, in order of increasing distance from the star). If we assume that the radio knot had this proper motion, we conclude that it was ejected about 1.8 years before the 1994.29 observations, that is, around 1992.5. Are there more recent optical observations of DG Tau B that reveal the appearance of a new knot? The most recent optical observations of the optical knots of DG Tau B reported in the literature were taken on 1998 February 23 and 24 with the Keck I telescope (Podio et al. 2011). In these data the closest knot is A1, at ≈3″ from the star. This is the same knot reported by Eislöffel & Mundt (1998) as the closest to the star in data taken a decade before. From the above assumptions, the radio knot was expected to be at $\approx 0\farcs7$ from the star in early 1998. It is then not surprising that it was not detected in the optical observations reported by Podio et al. (2011) because there is heavy obscuration in the NW optical lobe within $\approx 1\farcs2$ from the star (Stapelfeldt et al. 1997). However, at present (2012.0), the knot should be located at $2\farcs3$ from the star and is possibly detectable in new optical images.

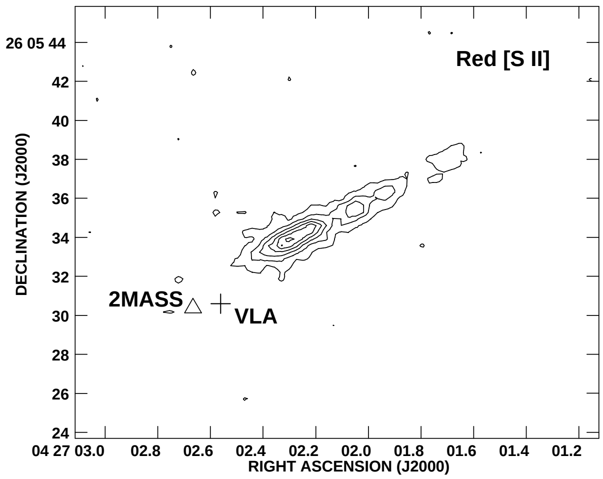

Fig. 3. Red [S II] image of the DG Tau B outflow. Contours are 15, 16, 17, 18, 19, and 20 times 101, in arbitrary units. The cross indicates the position of the VLA source and the triangle the position of 2MASS J04270266+2605304. The astrometry of the [S II] image has an accuracy of ∼1″.

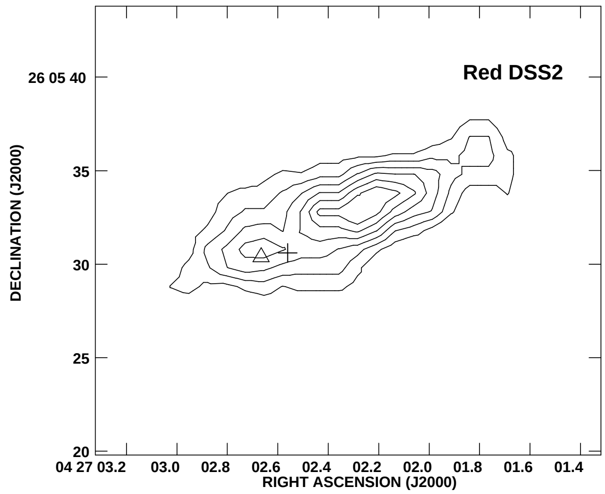

Fig. 4. Red image of the Second Digitized Sky Survey for the the DG Tau B region. Contours are 5.5, 6.0, 6.5, 7.0, 7.5, and 8.0 times 1010, in arbitrary units. The cross indicates the position of the VLA source and the triangle the position of 2MASS J04270266+2605304.

3. OPTICAL OBSERVATIONS

We have obtained an image of this object in the night of February 23, 2010. The narrow band image of DG Tau was obtained at the 2.6 m Nordic Optical Telescope (NOT) of the Roque de Los Muchachos Observatory (La Palma, Spain) using the Service Time mode facility. The image was obtained with the Andalucia Faint Object Spectrograph and Camera (ALFOSC) in imaging mode. The detector was an E2V 2K×2K CCD with a pixel size of 13.5 μm, providing a plate scale of 0.19 arcsec pixel^{-1}. A [S II] filter (central wavelength λ = 6725 Å, FWHM = 60 Å) was used to obtain an image of DG Tau in the [S II] 6716, 6731 Å emission lines.

Two exposures of 900 seconds each were combined to obtain the final image. The angular resolution during the observations, as derived from the FWHM of stars in the field of view, was of 0.9–1.0 arcsec. The images were processed with the standard tasks of the IRAF reduction package.

3.1. *Astrometry*

The [S II] image is shown in Figure 3. To locate the radio source in the optical image and discuss the relation between radio and optical sources, we did the astrometry of the image using the task XTRAN in AIPS. Since there were only four stars in the field, the astrometry is of modest quality, with an absolute positional error of order 1″. In this image we show the positions of the VLA source ($\alpha(2000)$ = 04^h 27^m $02\overset{s}{.}561; \delta(2000) = +26^\circ$ $05'$ $30\overset{''}{.}60$) and of the infrared source 2MASS J04270266+2605304 ($\alpha(2000)$ = 04^h 27^m $02\overset{s}{.}666; \delta(2000)$ = $+26^\circ$ $05'$ $30\overset{''}{.}38$), this last position taken from Skrutskie et al. (2006). This infrared source is usually considered to be the exciting source of the DG Tau B outflow. There is no [S II] emission within $2\overset{''}{.}3$ of the VLA or the 2MASS source. Under the assumption that the radio knot moves with the average proper motion of the five inner optical knots, we can conclude that either our hypothesis that the radio knot should be eventually detected in the optical is wrong, or that extinction is still very strong at these distances from the star and the knot will become visible only in the future. However, the radio knot could be moving at faster or slower proper motions. If it is moving much slower, it could still be hidden in the highly obscured region. If it is moving much faster it could, however, have caught up with the first old optical knot A1. This could lead to changes of the morphology and brightness of this knot in the new image, compared to the old images. However, the quality of the data does not allow a detailed comparison between images.

3.2. *Which object is the exciting source of the DG Tau B outflow?*

Interestingly, the positions of the VLA source and 2MASS J04270266+2605304 do not coincide, with the latter source being ≈1″ to the east of the former. To investigate this issue further, we superposed the positions of these sources on the red image of the Second Digitized Sky Survey (Figure 4). This optical image shows emission associated with the NW jet but also emission to the SE of the compact sources. While the VLA source seems to fall in the darkest part of the structure, 2MASS J04270266+2605304 appears to coincide with the SE structure. Tentatively, we propose that the VLA source traces the true exciting source, while 2MASS J04270266+2605304 could be an infrared reflection nebula associated with the SE lobe of the structure. This result is consistent with the conclusion of Mitchell et al. (1997), who found that the peak of the 2.6 mm dust continuum emission was displaced by $\sim 1\overset{''}{.}2$ to the NW of the "stellar" position of DG Tau B (Mundt, Brugel, & Buehrke 1987).

Also favoring the VLA object as the exciting source of the outflow is the fact that the accurate position of the dust millimeter emission reported by Guilloteau et al. (2011), that traces a disk around the star, coincides with the VLA position within $\approx 0\overset{''}{.}1$.

4. CONCLUSIONS

We have analyzed VLA and JVLA archive data to determine the proper motions of DG Tau B. These proper motions are consistent within error with those determined for the nearby young star DG Tau (Rodríguez et al. 2012). We show that the elongated radio structure observed by Rodríguez et al. (1995) corresponds to emission associated with the star plus a knot ejected in mid-1992. We propose that if this radio knot, no longer detectable in the radio, is producing detectable optical emission it could be observed as a "new" optical knot in future images.

There are two sources at the center of the outflow; one is the VLA source studied here and the other is the infrared source 2MASS J04270266+2605304. We propose that the true exciting source is the VLA object, while the infrared source is a reflection nebula.

L.F.R., S.A.D., L.A.Z., A.C.R. and J.C. are thankful for the support of DGAPA, Universidad Nacional Autónoma de México, and of Conacyt (Mexico). A.R. is partially supported by Spanish MCI grants AYA2008-06189-C03 and AYA2011-30228-C03, and FEDER funds. L.L. is indebted to the Alexander von Humboldt Stiftung and the Guggenheim Memorial Foundation for financial support. This research made use of the SIMBAD database, operated at CDS, Strasbourg, France. The Digitized Sky Survey image used in this paper was produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions. This paper is partially based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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