Dynamical Study of Exoplanet Host Stellar Systems: Upsilon Andromedae

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Abstract: The star υ Andromedae (50 And = HD 9826) is a high proper motion star of V = 4.10 and F8V spectral type, located at a distance of only 13.5 pc. Three exoplanets, υ And b, υ And c, υ And d, were detected between 1996 and 1999, and in 2011 a fourth planet was added to the system. This was the first multiple planetary system discovered. The star υ And has two optical wide companions, components B and C, at about 110 and 271 arcseconds. In 2002, Lowrance et al. detected a wide stellar companion, the D component, a M4.5V red dwarf star of V magnitude 14.1 with physical separation of about 55.6 arcsecond. In this work, digitized photographic plates and CCD images from online archives in addition to astrometric catalogs (2MASS, WISE) were used to increase the number of astrometric measures listed in literature. The linear elements for the optical components were calculated and the dynamical parameters for the physical AD pair were determined. A small relative motion with very low significance was detected for AD. This motion is compatible with a Keplerian motion and we conclude that AD components could be gravitationally bound.

1 Introduction

Currently more than 3500 exoplanets in more than 2600 planetary systems has been discovered by different techniques. About 13 per cent of these planets are found in stellar systems with two or more stars. Studying the dynamics of these stellar systems can contribute to increased knowledge about the exoplanet formation and evolution.

About 46 of these binary systems with exoplanets are very poorly studied with only one or two astrometric measures. Some of these pairs can be studied using modest instruments.

One of these poorly studied pairs is υ And AD (LWR 1 AD) of which the bright companion is a multiple planetary system of four planets. The D companion of υ And is a faint star of 14.1 magnitudes discovered by Lowrance, Kirkpatrick, and Beichman (2002) as a co-moving companion at a distance of about 55 arcseconds. It only has been measured twice, in 1998 (2MASS) and 2009 by James Daley (2011).

In this work, new astrometric measures were performed for the B, C, and D components with respect to υ And A. The new astrometric measures were obtained using photographic plates of Digitized Sky Survey (DSS), archived CCD images of the 2.0-m Faulkes Telescope North (FTN), and CCD images taken by one of us (Rafael Benavides). Finally, new astrometric measures were obtained using catalogs such as 2MASS and WISE.

A dynamical study is presented for the positions of the components with respect to υ And A.

The astrophysical properties determined in this work follow the guidelines published in Benavides et al. (2010).

The organization of this paper is as follows. In §2 some astrophysical properties for the primary component and the exoplanets are presented; Section §3 gives details of the astrometric measures. In §4 the weighting procedure is described. In §5 the method to obtain the linear elements for the optical companions is described. Section §6 details the results of our dynamical study. Finally, in §7 a summary and discussions are presented.

2 The Star υ Andromedae

υ And (= 50 And = HD 9826 = HIP 7513) is a high proper motion [$\mu(\alpha)$ = -173.3 mas yr^{-1} and $\mu(\delta)$ = -381.8 mas yr^{-1}] and a very near star (d = 13.5 pc) with V = 4.10 magnitude and F8V spectral type. Its metallicity is slightly richer than that of the Sun and its age is younger (about 3.0 Gyr). It has a radial velocity of -28.6 km s^{-1}.

In previous years there have been several efforts to detect close companions around υ And. These works searched for stellar/substellar companions closer than 25". Baines et al. (2008) used the High Angular Resolution Astronomy (CHARA) Array, located on Mount Wilson, California, to observe υ And to search for stellar companions with separations of less than 1 mas to 50 mas. The observation of υ And showed systematic errors in their measurements that could suggest an unseen stellar companion. However, no companion was detected.

Tanner et al. (2010) performed high-angular resolution observations with the Palomar Observatory Hale 5-m Telescope using the PHARO near-IR camera with the Palomar adaptive optics (PALAO) system. It used a 25 mas/pixel scale camera (25" field of view) and at 0.45" radius occulting spot.

Roberts et al. (2011) observed υ And using the AEOS 3.6m telescope and its AO system. The CCD images have a field of view of 10" and a scale of 22 mas/pixel. The FWHM was of about 0.13. The widest detectable separation is about 5".

Mason et al. (2011) used the USNO speckle camera on the 4.0-m Kitt Peak National Observatory. No companion was detected within the ranges $\Delta m_V < 3$, and $0.03 < \rho < 1.5$ arcsecs.

In 2007-2008 Hulsebus et al. (2014) observed υ And using the InfraRed Array Camera onboard the Spitzer Space Telescope, with a scale of 1.22 as/pixel, able to detect substellar companions at a separation of 10 - 25 arcsecs.

Butler et al. (1997) detected Keplerian Doppler velocity variation in υ And that corresponded to a giant planet (υ And b) of 0.5 Jupiter mass with an orbital period of 4.61 days and a radius of 0.057 AU. In addition, Butler et al. also noted evidence of variability in Vγ (systemic velocity). This variability was confirmed by Butler et al. (1999) and it is consistent with Keplerian orbital motion of two planets (υ And c and d) with orbital period of 241 and 1281 days and mass of 1.8 and 10 Jupiter mass in moderate eccentric orbits. At that time, it was the first multiple planetary system discovered around a main sequence star. Lastly, Curiel et al. (2011) detected a fourth planet (υ And e) with a mass of 1 Jupiter mass, and a period of 3849 days. υ And is the fifth system to contain at least four planets.

3 Astrometric Observations

In this work, new astrometric measures were performed for the B, C, and D components of the system with respect to υ And. The new astrometric observations were obtained using photographic plates of Digitized Sky Survey (DSS), archived CCD images of the 2.0 m FTN, and CCD images taken by one of us (Rafael Benavides) in southern Spain. Finally new astrometric measures were obtained using catalogs such as 2MASS and WISE.

These measures are listed in Table 1, which shows the pair in column (1), the observational epoch and the θ and ρ values in columns (2) - (4). θ values are expressed for the 2000 equinox. Columns (5) - (8) give the number of nights (N), the author of the measure, the aperture of the telescope (in meters), and the observational method in the USNO system. Finally, the last column gives the origin of the measure.

3.1 Photographic plates from Digitized Sky Survey

Digitized Sky Survey comprises a set of all-sky photographic surveys in E, V, J, R, and N bands conducted with the Palomar and UK Schmidt telescopes. The astrometric measures were problematic because υ And appears very saturated on all the plates.

A good method was to use the spikes of υ And on the plates to obtain a good estimate of its centroid. This was done using *fv* tool, a FITS viewer and editor tool developed at the High Energy Astrophysics Science Archive Research Center (HEARSAC) at NASA/GSFC. This tool can plot isolevel curves that show clearly the position of the spikes of the bright star and the centroid for the weak companions (Figure 1). The values of the RMS (root mean square) residuals were of aceptable accuracy (0.3" for the angular distance, ρ) taking into account the saturated status of the primary.

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Table 1. Astrometric measures for WDS 01368+4124

Pair	Epoch	θ (deg)	ρ (")	N	Author	Aperture	Method	Origin
BUP 23AB	1909.51	128.40	114.00	3	Bu_1913	1.0	Ma	(WDS)
	1953.709	119.97	111.89	1	Rica	1.2	Pp	POSS-E Red Plate
	1953.709	119.65	110.53	1	Rica	1.2	Pp	POSS-I O
	1983.705	113.30	109.97	1	Rica	1.2	Pp	Quick-V Northern
	1989.766	112.04	110.47	1	Rica	1.2	Pp	POSS-II Red 2.
	1989.766	111.90	110.40	1	Rica	1.2	Pp	POSS-II Red.
	1992.683	111.30	110.61	1	Rica	1.2	Pp	POSS-II Blue
	1993.791	111.50	109.67	1	Rica	1.2	Pp	POSS-II N
	1995.866	110.10	110.17	1	Rica	1.2	Pp	POSS-II N
	1998.837	110.23	110.53	1	TMA2003	1.3	E2	(WDS, 2MASS)
	2005.8051	108.55	110.54	1	Rica	2.0	E	Faulkes Telescope
	2009.983	107.80	110.28	1	Dal2011	0.2	C	(WDS)
	2010.5	107.66	110.66	1	Rica	0.4	Hw	WISE
	2015.0675	106.45	110.94	2	Rica	0.3	C	Images of Benavides
STF 554 AC	1853.76	277.2	286.83	1	Stt1893a	0.4	Ma	(WDS)
	1882.61	280.0	283.80	1	Stt1893a	0.4	Ma	(WDS)
	1903.814	281.6	280.19	3	Com1908	0.4	Ma	(WDS)
	1915.83	282.6	279.25	2	Com1929	0.4	Ma	(WDS)
	1924.017	283.2	278.34	2	Dic1963b	0.7	Ma	(WDS)
	1925.87	283.4	291.00	3	Sky1927	0.3	Ma	(WDS)
	1991.71	289.4	273.61	1	TYC2002	0.3	Ht	(WDS)
	1998.84	290.0	273.22	1	TMA2003	1.3	E2	(WDS)
	2006.885	290.8	271.56	1	Arn2007b	0.2	Mg	(WDS)
	2015.0679	291.49	272.16	2	Rica	0.3	Cl	Images of Benavides
LWR 1 AD	1953.709	149.00	55.44	1	Rica	1.2	Pp	POSS-E Red Plate
	1953.709	149.08	55.62	1	Rica	1.2	Pp	POSS-I O
	1983.705	148.57	55.83	1	Rica	1.2	Pp	Quick-V Northern
	1989.766	148.62	55.52	1	Rica	1.2	Pp	POSS-II Red 2.
	1989.766	148.31	55.94	1	Rica	1.2	Pp	POSS-II Red.
	1992.683	148.85	55.27	1	Rica	1.2	Pp	POSS-II Blue
	1993.791	148.61	55.76	1	Rica	1.2	Pp	POSS-II N
	1995.866	148.35	54.69	1	Rica	1.2	Pp	POSS-II N
	1998.837	148.60	55.63	1	2MASS	1.3	E2	(WDS)
	2005.805	148.60	55.59	1	Rica	2.0	E	Faulkes Telescope North
	2009.983	148.70	55.38	1	Dal2011	0.2	C	(WDS)
	2010.5	148.90	55.53	1	Rica	0.4	Hw	WISE
	2015.069	148.94	55.57	2	Rica	0.3	C	Images of Benavides

We assumed the same error for tangential direction (theta values).

3.2 Archived CCD images from 2.0-m FTN

The authors used the online CCD images taken with the Faulkes Telescope North (FTN)†. This telescope is located at Haleakala Observatory in the U.S. state of Hawaii. It is a 2.0 m (79 in) f/10 Ritchey-Chrétien telescope owned and operated by *Las Cumbres Observatory - Global Telescope*. It is used by researchers and education groups around the globe.

For υ And stellar system, we have found three Bessel B, V and R CCD images of 1 second duration, taken on October 21, 2005 between 06:56 and 06:57 UTC (epoch 2005.8051). The imaging camera was a DillCam camera, with a chip of 2048 x 2048 pixels of 13.5 micrometers.

† *http://sci-archive.lcogt.net/cgi-bin/ft_search*

The downloaded FITS images were not readable by REDUC or Astrometrica software, but they were readable by the ALADIN virtual observatory tool. We opened the FITS images with ALADIN and then we exported the results and saved them as FITS images. This operation changed the internal codification of the original FITS images. This allowed REDUC and Astrometrica to open the images. The original images have no astrometric frame within the FIT header, and so we needed to calibrate them. Astrometrica software could not be used because there were not enough stars in the images. We did a manual calibration using the 6 stars detected in the images and listed in the WISE catalog with astrometric data for approximately 2010.5 (Figure 2). All the stars have proper motion smaller than 18 mas yr^{-1}. We used the scale of the image specified within the FITS header (0.27837 ± 0.0003 arcsec $pixel^{-1}$).

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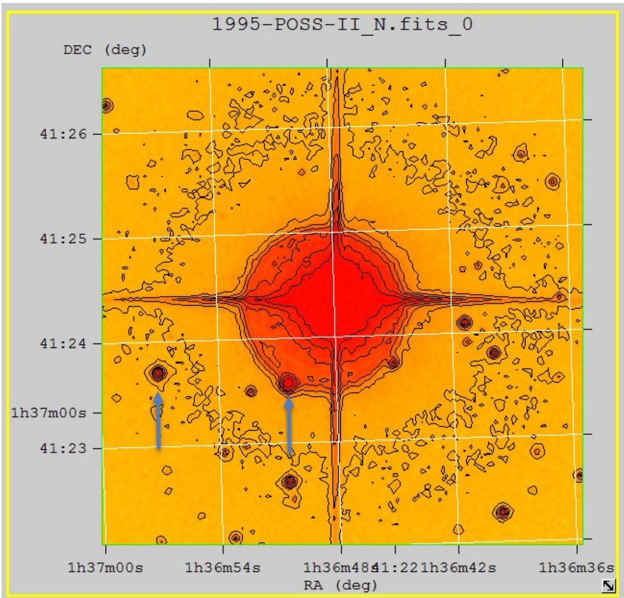

Figure 1. fv tool with the isolevel curves showing the spikes. Components B and D (the inner star) are indicated with blue arrows.

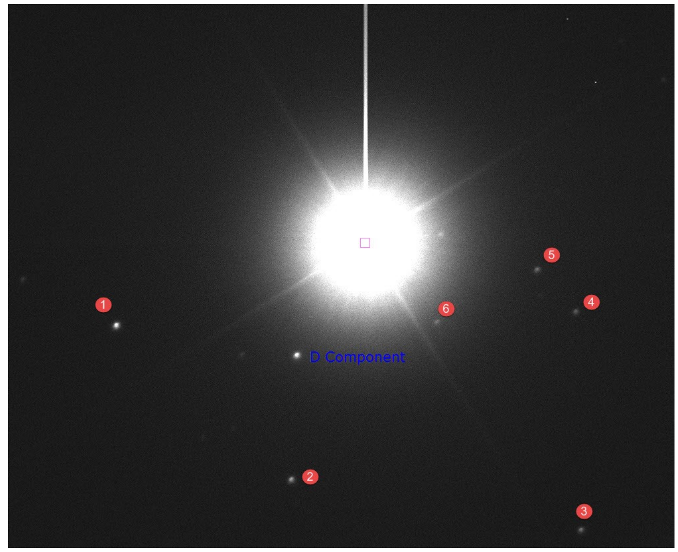

Figure 2. υ And on CCD image taken with the 2.0 m FTN. The six stars used for manual calibration are shown. The D component is indicated.

The orientation determined by our calibration process was -0.09 ± 0.04 deg. The field of view of the images was 9.5 x 9.5 minutes of arc.

The individual astrometric measures using FTN images are detailed in Table 2. The position angles and angular distances were obtained using REDUC† software, developed by Losse (2010). Although the bright primary component was saturated, REDUC obtained an astrometric procedure that allows us to obtain a good centroid if the unsaturated part of the PSF is within the input box. The radial and tangential errors were estimated as 10% of the scale added quadratically to the calibration errors.

In this work, due to the heavy saturation of the primary star, we assumed that the RMS residuals for the angular distance and position angle are similar to those for the DSS plates, about 0.3 arcsecond.

Table 2. Astrometric Measures for Upsilon Andromedae with Faulkes Telescope North

Pair	Filter	Theta	Rho
BUP 23AB	Clear	108.44 ± 0.07	110.32 ± 0.14
	V band	108.61 ± 0.07	110.67 ± 0.14
	B band	108.59 ± 0.07	110.63 ± 0.14
	Mean	**108.55 ± 0.09**	**110.54 ± 0.19**
LWR 1AD	Clear	148.58 ± 0.09	55.37 ± 0.08
	V band	148.62 ± 0.09	55.80 ± 0.08
	Mean	**148.60 ± 0.09**	**55.59 ± 0.30**

†*http://www.astrosurf.com/hfosaf*

3.3 CCD images of Posadas Observatory

Rafael Benavides used the IAU MPC J53 Observatory in Posadas, which is a town in Southern Spain, using an ASCOM QHY9 camera attached to a 0.3-m (11 inches) Celestron telescope with a focal length of 1,292 mm. QHY9 is a classic monochrome camera using the very popular 8.6 mega pixel KAF8300 CCD sensor with 3448 x 2574 pixels of 5.4 μm. On January 24 and 25, 2015, υ And system was imaged. The field of view is 48.1' x 35.9'. On January 24 at about 20:00 UT, 62 CCD images of 0.2 seconds of exposure time were combined into one final image. On January 25th two series of images (with 3 and 5 individual images) were taken, one with 0.5 seconds of exposure and the other with 1 second. The small exposure time had the objective of reducing the saturation of υ And. The calibration of the images was performed with Astrometrica software. The scale was improved using an excel tool designed by Francisco Rica to give 4 - 5 decimals (Astrometrica only gives two decimals). Due to the saturation, Astrometrica was not used to measure υ And. We used REDUC software because the algorithm used to determine the centroids is not much affected by saturation. This algorithm used the unsaturated part of the PSF to yield a good astrometric determination. Figure 3 shows one of the CCD images taken by Rafael Benavides.

Table 3 lists the individual astrometric data for each night and series of images. The errors are the standard

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Table 3. Astrometric Measures for υ Andromedae system from Posadas

Pair	Epoch	Theta	Rho
BUP 23AB	2015.0662	106.35	110.82±
	(0.5 s) 2015.0688	106.53 ± 0.01	111.00± 0.04
	(1.0 s) 2015.0688	106.47 ± 0.07	111.01± 0.09
MEAN	**2015.0680**	**106.45 ± 0.09**	**110.94± 0.11**
STT 554AC	2015.0662	291.49 ±	272.22±
	(0.5 s) 2015.0688	291.49 ± 0.01	272.15± 0.02
	(1.0 s) 2015.0688	291.49 ± 0.02	272.11± 0.07
MEAN	**2015.068**	**291.49 ± 0.02**	**272.16± 0.07**
LWR 1AD	2015.0662	149.13	55.56
	(0.5 s) 2015.0688	148.83 ± 0.06	55.60± 0.08
	(1.0 s) 2015.0688	148.85 ± 0.07	55.54± 0.07
MEAN	**2015.0680**	**148.94 ± 0.17**	**55.57± 0.08**

deviations. The orientation of the images was -0.34 ± 0.01 deg and the scale was 0.8619 ± 0.0003 a.s. pixel^{-1}.

4 The Weighting Procedure

The weighting procedure of the observations is an important part in the dynamical analysis. For all the astrometric measures performed in this study using DSS photographic plates, we calculated the O-C residuals with respect to the linear fit. The mean RMS (root mean square) residual is about 0.3 arcsec for ρ. We assumed that the same error is valid for the tangential direction. This RMS is similar to others pairs measured by the authors using DSS plates and saturated primaries. The same error was assumed for the image taken by the Faulkes Telescope North in view of the dispersion of the measures for the 3 individual images. For the error in the relative astrometric using 2MASS and WISE catalogs, the listed error in AR and DEC were used. The error for the 2MASS measures was similar to those using DSS plates. The WISE astrometry was of higher precision (0.05-0.10"). The weights are calculated using the standard formula $1/\sigma^2$.

5 Calculating the Linear Elements

We calculate the rectilinear elements in Cartesian coordinates (see the recommendation in the *Catalog of Rectilinear Elements* (Hartkopf et al. 2006, hereafter Lin 1)) using an excel tool called VM_LINEAR30 and designed by one of us (Herny Zirm).

The conversion of the resulting rectangular elements to Cartesian elements was done according to the formulas of Debehogne & Freitas Mourao (1977).

The translation of the specified symbols is described in Table 4.

For the calculations of the linear motions, the following formulas are defined:

$$\rho_i \cos\theta_i = \Delta\mu\delta(t_i - t_m) + \rho_m \cos\theta_m$$
$$\rho_i \sin\theta_i = \Delta\mu\alpha_{\cos\delta}(t_i - t_m) + \rho_m \sin\theta_m$$

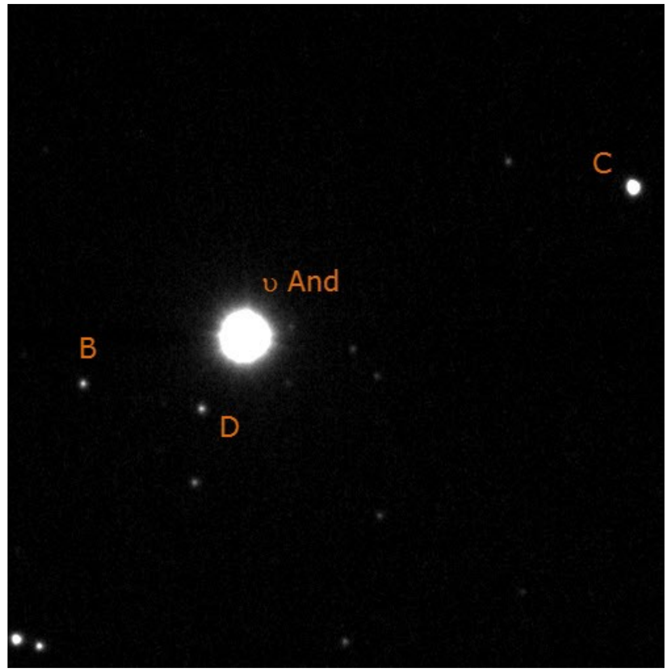

Figure 3. CCD image taken by Rafael Benavides on 2015 January 25th.

Table 4: Conversion Debehogne & Freitas Mourao (1977) - LIN1 catalog

This paper	Debehogne & Freitas Mourao (1977)	LIN1	value
Right ascension difference during closest approach, component B-A = $\Delta\alpha_{\cos\delta}$	$\rho_0 \sin\theta_0$	X_0	["]
Mean yearly motion in Right ascension = $\Delta\mu\alpha_{\cos\delta}$	v_Y	X_A	["/yr]
Declination difference during closest approach, component B-A = $\Delta\delta$	$\rho_0 \cos\theta_0$	$(-1)*Y_0$	["]
Mean yearly motion in Declination = $\Delta\mu\delta$	v_X	$(-1)*Y_A$	["/yr]

The index *m* defines the mean epoch of the used measurements. Then solve the weighted equations; the unknowns are in brackets:

$$\sqrt{w_\delta}\,\rho_i \cos\theta_i = [\Delta\mu\delta]\sqrt{w_\delta}(t_i - t_m) + [\rho_m \cos\theta_m]\sqrt{w_\delta}$$
$$\sqrt{w_\alpha}\,\rho_i \sin\theta_i = [\Delta\mu\alpha_{\cos\delta}]\sqrt{w_\alpha}(t_i - t_m) + [\rho_m \sin\theta_m]\sqrt{w_\alpha}$$

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The derived quantities are:

$$\theta_0 = \arctan \frac{-\Delta\mu\delta}{\Delta\mu\alpha_{\cos\delta}}$$

$$\rho_0 = \rho_m \cos\theta_m \cos\theta_0 + \rho_m \sin\theta_m \sin\theta_0$$

$$t_0 = \frac{\rho_0 \cos\theta_0 - \rho_m \cos\theta_m}{\Delta\mu\delta} - t_m = \frac{\rho_0 \sin\theta_0 - \rho_m \sin\theta_m}{\Delta\mu\alpha_{\cos\delta}} - t_m$$

$$\Delta\mu = \sqrt{(\Delta\mu\alpha_{\cos\delta})^2 + (\Delta\mu\delta)^2}$$

$$\Delta\alpha_{\cos\delta} = \rho_0 \cos\theta_0$$

$$\Delta\delta = \rho_0 \sin\theta_0$$

6 Dynamical Study

A dynamical study is described and the linear elements were determined for the B and C background optical components.

The astrophysical properties estimated in this work for B and C components follow the guidelines published in Benavides et al. (2010). The multiband photometry (*B*, *V* from APASS; *J*, *H*, *K* from 2MASS; and *W1*, *W2* from WISE) were fitted, minimizing χ^2, to the empirical tables of Mamajek† which relates the mean multiband colors with the corresponding astrophysical parameters (spectral types, absolute magnitudes, effective temperatures, masses, etc.).

The reddening in the line of sight was estimated using the maps of Schlegel, Finkbeiner, and Davis (1998) and the more recent of Schlafly and Finkbeiner (2011)††. The resulting values were scaled to the initial distance using the formula published by Anthony-Twarog, and Twarog (1994).

This procedure was performed using an Excel tool, called *Mamajek tool v1.2.xlsx*, designed by Francisco Rica.

6.1 The Pair BUP 23 AB

In 1897 a 40-inch refractor telescope was mounted in the Yerkes Observatory. S. W. Burnham was living in Chicago and the Yerkes Observatory was located several hours away by train and Burnham could use the telescope during the weekends. The *Burnham Double Star Catalog* (BDS) was published in 1907. He then started another great work. Between 1907 and 1912 Burnham performed about 9,500 measures of wide (and unequal) pairs to study proper motions. One of these pairs was BUP 23 AB. This double was cataloged in 1909 (at this time he was 71 years old!) when he found a star of 12.7 magnitude at 114 arcsecs from the bright υ And in direction 128.4 deg. Burnham performed in total three measures as was his custom in this last project.

One hundred years later another observer, James Daley, also an amateur from USA, again measured this pair. He used a CCD camera and noted an important change in position, as was expected. A third measure came from the 2MASS project in 1998. In this work, the number of astrometric measures was increased by 11. These measures were obtained using photographic plates from the Digitized Sky Survey, CCD images from 2.0-m FTN, CCD images obtained by Rafael Benavides of Posada Observatory, and the WISE catalog. In total, the 14 measures covered a time baseline of 106 years. A dynamical study yields a relative motion of 408.8 ± 3.1 mas yr^{-1} close to the total proper motion of υ And (419 mas yr^{-1}) and in the opposite direction. The B star is clearly a background component. The linear elements are listed in Table 5 and the plot in Figure 4. The astrometric RMS residual is 0.20º and 0.25" for θ and ρ, a good result taking into account the saturation of the bright main component. The ephemerides for 2016 are 106.43 ± 0.12º and 110.94 ± 0.18".

The B component is a faint star with a small proper motion. The UCAC4 catalog lists the APASS photometry (*V* = 13.10 ± 0.04 and *B-V* = +0.58 ± 0.07). In this work we determined for the first time a reddening of E (*B-V*) = 0.06 and Av = 0.22 magnitudes, a F7V: spectral type, and a photometric distance of about 657 pc.

6.2 The pair STT 554 AC

The C component, a star of 10.37 magnitude, was included in the system in 1853 by Otto Struve of Pulkovo Observatory. The position at that date was 277.2 deg and 286.83". In 1882 Otto Struve performed a second measurement. Both measures were published in 1893. This pair was neglected from 1925 to 1991. In the WDS catalog, there are 9 astrometric measures. The last measure was performed by amateur Dave Arnold in 2006 (290.8 deg and 271.56"). In this work, we added a new astrometric measure for 2015.0679, obtained using CCD images taken by Rafael Benavides.

All these astrometric measures were used to perform the dynamical study. The time baseline was 161 years. The dynamical study yields a relative motion of 423.7 ± 4.1 mas yr^{-1} very close to the total proper motion of ν And in the opposite direction. The C star is clearly a background optical component. The linear elements are listed in Table 6 and the plot in the Figure 5. The RMS residual is of 0.06º and 0.19". The ephemerides for 2016 is 291.55 ± 0.04º and 272.32 ± 0.17".

The C component is a faint star with a small proper

(Text continues on page 492)

† http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.dat

†† Online calculating using the web http://irsa.ipac.caltech.edu/applications/DUST/

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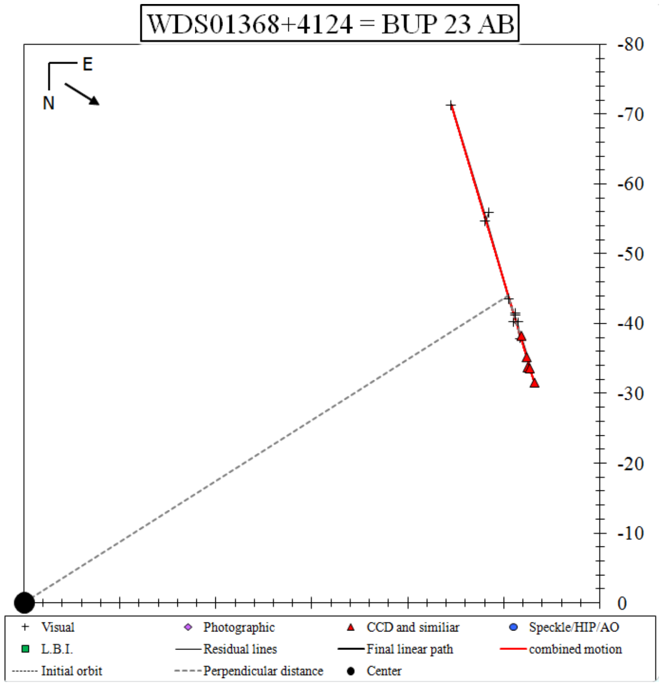

Figure 4. Linear path for BUP 23 AB

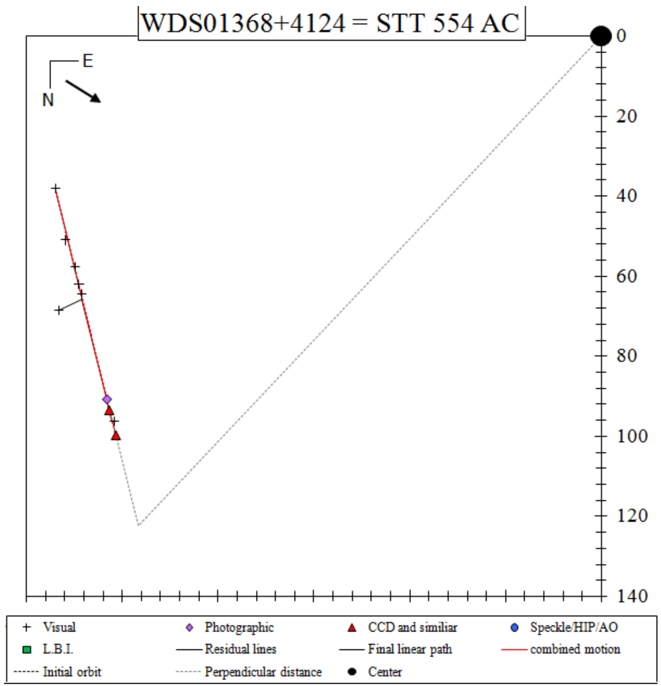

Figure 5. Linear path for STT 554 AC

Table 5. Linear Elements for BUP 23 AB

WDS 01368+4124 = BUP 23 AB	
WDS	01368+4124
Name	BUP 23 AB
	upsilon And
HD	9826
HIP	7513
Calculated	
$X_0 = \Delta\delta$ ["]	-43.99 ± 0.54
$\mu_X = \mu_\delta$ ["/yr]	0.3747 ± 0.0022
$Y_0 = \Delta\alpha_{\cos\delta}$ ["]	100.91 ± 0.25
$\mu_Y = \mu_{a\cos\delta}$ ["/yr]	0.1634 ± 0.0022
Derived Properties	
t_0	1982.35 ± 1.54
ϑ_0 [°]	113.55 ± 0.31
ρ_0 ["]	110.079 ± 0.081
μ_{XY} ["/yr]	0.4088 ± 0.0031
first obs.	1909.51
last obs.	2015.0675
# obs.	14 / 14
Other Quantities Pertaining to the Fit	
rms ϑ [°]	0.20
rms ρ ["]	0.249
MA ϑ [°]	0.12
MA ρ ["]	0.175
rms ϑ ["]	0.394
rms ρ [°]	0.13
MA ϑ ["]	0.232
MA ρ [°]	0.09

Table 6. Linear Elements for BUP 23 AC

WDS 01368+4124 = STT 554 AC	
WDS	01368+4124
Name	STT 554 AC
	ups And AC
HD	9826
HIP	7513
Calculated	
$X_0 = \Delta\delta$ ["]	122.52 ± 1.87
$\mu_X = \mu_\delta$ ["/yr]	0.3780 ± 0.0020
$Y_0 = \Delta\alpha_{\cos\delta}$ ["]	-241.89 ± 0.95
$\mu_Y = \mu_{a\cos\delta}$ ["/yr]	0.1915 ± 0.0035
Derived Properties	
t_0	2075.57 ± 5.09
ϑ_0 [°]	296.86 ± 0.44
ρ_0 ["]	271.150 ± 0.098
μ_{XY} ["/yr]	0.4237 ± 0.0041
first obs.	1853.76
last obs.	2015.0679
# obs.	10 / 10
Other Quantities Pertaining to the Fit	
rms ϑ [°]	0.06
rms ρ ["]	0.188
MA ϑ [°]	0.04
MA ρ ["]	0.171
rms ϑ ["]	0.315
rms ρ [°]	0.04
MA ϑ ["]	0.189
MA ρ [°]	0.04

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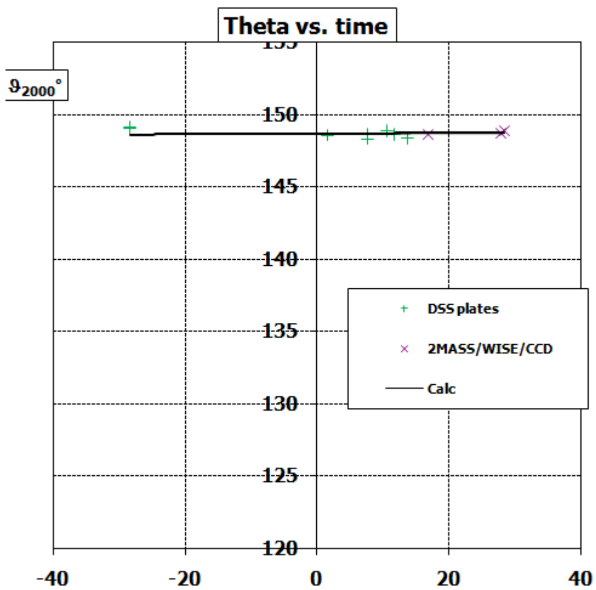

Figure 6. Plot of theta vs time for LWR 1 AD

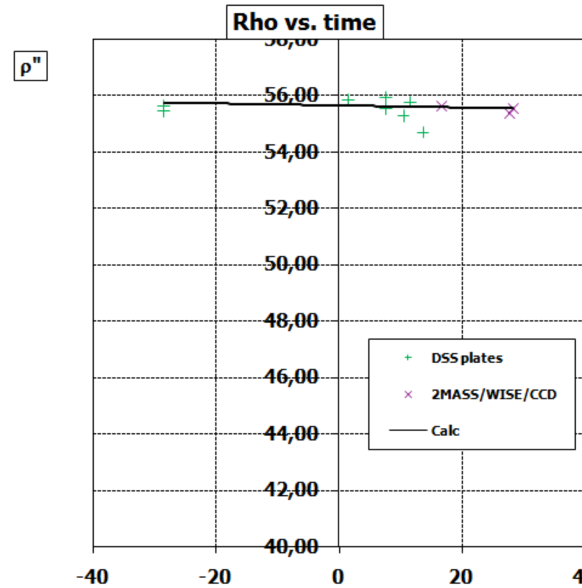

Figure 7. Plot of rho vs time for LWR 1 AD

(Continued from page 490)

motion. The UCAC4 catalog lists APASS photometry of V = 10.29 ± 0.01 and B-V = +0.42 ± 0.03. The reddening calculated in this work is E(B-V) = 0.03 and Av = 0.12 magnitudes. Our study determines a F4V: spectral type and a photometric distance of about 250 pc.

6.3 The Common Proper Motion System LWR 1 AD

A common proper motion companion of V = 14.1 magnitude (APASS), was detected by Lowrance et al. (2002) and is located 55 arcseconds from the bright component. A. Lowrence et al. determined the comoving nature from examination of POSS I and II plates (epochs 1953 and 1995), plus 2MASS. They determined the spectral type of the companion to be M4.5V. The component D is listed in the Simbad database as 2MASS J0136504+412332. Only two astrometric measures are listed in the WDS catalog: one from the 2MASS project in 1998 and one micrometric measure performed by Dave Arnold in 2009. In this work, an additional 11 astrometric measures were obtained using digitized photographic plates from the Digitized Sky Survey, CCD images from the archive of FTN, CCD images taken by Rafael Benavides, and the WISE catalog. In total, 13 astrometric measures with a time baseline of 61 years (from 1953 to 2015) were used to perform the dynamical study that yielded a relative motion of 0.005 ± 0.003 deg yr^{-1} and +1.9 ± 2.0 mas yr^{-1} for θ and ρ. The total relative motion is +4.2 ± 2.5 mas yr^{-1}. Figures 6 and 7 plot the evolution of θ and ρ and Table 7 lists other positional and dynamical data. The RMS residual is 0.12º and 0.07". At the distance of υ And, the relative and projected velocity was 0.27 ± 0.12 km s^{-1}. A Monte Carlo approach shows that for 100.00% of simulations the relative projected velocity (assuming differential radial velocity Vz of 0 km s^{-1}) is smaller than the escape velocity (V_{esc})†. Thus, the components A and D could be gravitationally bound, even for Vz ≤ 1.86 km s^{-1}. Despite this result, the relative motion detected has a very low significance (about 1σ) and we must wait for GAIA to improve the dynamical results.

In addition to the common proper motion and a dynamic compatible with a Keplerian motion, the component D has 2MASS infrared flux and colors consistent with a mid-M dwarf at the distance of υ And (Lowrance et al. 2002).

The physical projected separation is approximately 749 AU. Using the Hauser and Marcy (1999) orbital method with the centroid values of the dynamical parameters determined in this work, an orbital period (P) greater than 6200 years and a semimajor axis (a) of 28.6" (385.9 UA) was determined.

7 Summary and Discussions

The exoplanet host stellar system υ And is a solar-type, bright star with high proper motion located at a distance of only 13.5 pc. The star υ And has two optical wide companions listed in the WDS catalog. These are the components B and C, located at about 110 and 271 arcseconds and with magnitudes V of 13.1 and 10.3. The D component was detected in 2002 by Lowrance et

† Only a V_{esc} for a face-on orbit (where r = s) was calculated. This is the upper limit for the V_{esc}.

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Table 7. Astrometric, Dynamical, and Velocity Data

Data	Value
Epoch	1984.389
θ (°)	148.77 ± 0.08
ρ (arcsec)	55.48 ± 0.05
x (AU)	+387.8 ± 1.0
y (AU)	-640.3 ± 1.6
$d\rho/dt$ (mas yr^{-1})	+1.9 ± 2.0
$d\theta/dt$ (deg yr^{-1})	+0.005 ± 0.003
dx/dt (mas yr^{-1})	-2.3 ± 2.3
dy/dt (mas yr^{-1})	-3.5 ± 2.1
V_x (km s^{-1})	-0.14 ± 0.14
V_y (km s^{-1})	-0.22 ± 0.13
V_z (km s^{-1})	...
$V_{esc-max}$ (km s^{-1})	1.89 ± 0.08
M_A ($M_\odot$)	1.2
M_B ($M_\odot$)	0.3
Distance (pc)	13.49 ± 0.03

al. (2002) and shares a proper motion with the bright companion. It is an M4.5V red dwarf of *V* magnitude 14.1 with apparent separation at about 55.6 arcseconds. The AB and AD pairs were very poorly studied. We used digitized photographic plates and CCD images in addition to astrometric catalogs (2MASS, WISE) to increase the number of astrometric measures. The linear elements for the AB and AC pairs were calculated.

The D component has the same proper motion as υ And. In addition, its photometric data is compatible with a star located at the same distance as its bright companion. The projected physical separation of AD is about 750 AU. The dynamical parameters show a very small relative motion (with a 1σ significance level) that at the distance of the system corresponds to a relative projected velocity of 0.27 ± 0.12 km s^{-1}. This motion is compatible with a Keplerian motion (escape velocity of 1.89 ± 0.08 km s^{-1}) although the radial velocity of D component (V_z) is unknown. This data will help us to determine the total relative velocity of D with respect to υ And, increasing the evidence that favors the gravitationally bound status.

Acknowledgements

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This publication has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory. Brian Mason kindly supplied astrometric information.

This research has made use of "Aladin sky atlas" developed at CDS, Strasbourg Observatory, France.

The Digitized Sky Surveys were 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.

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