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A B S T R A C T

New orbital period variation of the eclipsing binary, AD Andromeda, was analyzed based on one CCD photometric times of minimum we have obtained and all available photoelectric and CCD values collected from the literatures. It is discovered that the orbital period of the binary shows a periodic oscillation with a period of 14.38 years and an amplitude of 0.0186 days. The periodic oscillation can be explained by the light-time effect via the presence of a tertiary component in a nearly circular orbit with a small eccentricity of $e = 0.30$ in the system. Based on the present analysis, it is estimated that the mass of the third body is no less than $1.76(\pm 0.08)\ M_\odot$, and it should contribute light to the total system. Meanwhile, the photoelectric light curve obtained in yellow light by Ruciński [Ruciński, S.M., 1966. AcA 16, 307] was reanalyzed with the 2003 version of the W–D code. The results show that AD Andromeda is a detached eclipsing binary, and photometric solutions were computed. Based on the analysis, we obtained a small amount of third light in the system ($L_{3V} \sim 0.001$), which is too small for the contribution of the tertiary companion star. The low luminosity of the third companion may be explained in two possible ways, either: (1) the third companion might itself be a close double star consisting of two stars of 0.88 solar masses, or (2) it is a dark star such as a neutron star. We think the first possibility is a more likely one than a neutron star companion. New photometric and spectroscopic observations and a detailed investigation of those data are urgently required in the future.

1. Introduction

AD Andromeda (BD +47°4207, $V_{\max} = 11.2mag$) is an interesting system with two nearly identical members, whose spectral type was previously classified as F-type (Koch et al., 1970). Later, it was classified as A0V type by Hill et al. (1975) in their spectral study. The light variability of AD Andromeda was discovered by Guthnick and Preger (1927). It was found that the photographic magnitude ranging from $10.^{m}8$ to $11.^{m}7$ and with almost the same two minima. The observational data were later analyzed by Gaposchkin (1932) who gave approximate geometrical elements of the system. Then, it was reobserved visually and photographically by Taylor and Alexander (1940) and Briede (1949). The first photoelectric light curve in yellow light was obtained by Ruciński (1966), five times of light minimum were given in that paper. Ruciński (1966) roughly analyzed the light curve with the method of Russell and Merril (1952), he obtained different results from Gaposchkin's (1932) (based on photographic observations). The light curve obtained by Ruciński (1966) was reanalyzed by Giuricin and Mardirossian (1981) with Wood's (1972) lightcurve synthesis computer model, they rediscuss the photometric elements of AD Andromeda, the results revealed that both components of the system were practically identical with equal sizes, masses, temperatures, and luminosities, and they gave indeterminate orbital inclination $i = 81^{\circ}.9 \pm 0.^{\circ}4$.

The period variations of AD Andromeda had been investigated by Whitney (1957), Ruciński (1966), and Frieboes-Conde and Herczeg (1973). Based on all visual or photographic light minimum derived before 1973 and only five photoelectric light minimum obtained by Ruciński (1966), Frieboes-Conde and Herczeg (1973) determined the period of the triple system 16.8 yr with an amplitude of $A_3 = 0.^{d}0275$, and a mass function of $f(m) = 0.382\ M_\odot$. (estimated the mass of the binary based on F3V + F7V). In the present paper, the light-time effect of AD Andromeda was analyzed based on all available photoelectric and CCD times of light minimum. The physical properties of the third body are discussed. Moreover, the light curve obtained by Ruciński (1966) was reanalyzed with the 2003 version of the W–D code. New photometric solutions of the system were derived.

2. New CCD photometric observations for AD Andromeda

In order to analyze the period variations of the binary stars and investigate the physical properties of the third body, AD Andromeda

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Table 1
Coordinates of AD Andromeda, the comparison, and the check stars

Stars	α_{2000}	δ_{2000}
AD Andromeda	$23^h36^m45.07^s$	48°40′16.0″
The comparison	$23^h36^m56.65^s$	48°41′14.8″
The check	$23^h36^m34.34^s$	48°38′54.9″

was observed on December 23, 2007 with the PI1024 TKB CCD photometric system attached to the 1.0-m reflector at the Yunnan Observatory. The R filter, close to the standard Johnson UBV system, was used. The effective field of view of the photometric system is about 6′.5×6′.5 at the Cassegrain focus and the size of each pixel is 0″.38. The integration time is 30 s for each image. The coordinates of the variable star, the comparison star, and the check star are listed in Table 1. The PHOT (measure magnitudes for a list of stars) of the aperture photometry package of IRAF was used to reduce the observed images. By using our photometric data, one time of minimum light, HJD 2454458.0635(±0.0002), was determined.

3. Orbital period variation of AD Andromeda

The period variations of AD Andromeda had been investigated by Whitney (1957), Ruciński (1966), and Frieboes-Conde and Herczeg (1973). In this paper, in order to investigate the physical properties of the third body in AD Andromeda, we intend to reanalyze the period variation and to search for cyclic period change of the eclipsing binary star. A total of 48 photoelectric or CCD times of light minimum from the literature (we have gotten rid of the value 2450368.3160(±0.007) obtained by Paschke Anton (1997) because of its large error), together with one obtained by us, have been collected and compiled in the present paper. They are listed in the first column of Table 2. Those shown in the third column are the observational method where "pe" refers to photoelectric photometry and "CCD" to charge-coupled device photometry.

Using the following ephemeris given by Kreiner et al. (2001):

$$\mathrm{Min.}I = HJD2439002.4445 + 0.98619443E, \tag{1}$$

we computed the $(O-C)_1$ values for these times of light minimum, and the $(O-C)_1$ values are listed in the sixth column of Table 2. The corresponding $(O-C)_1$ curve is shown in Fig. 1. It is showed from the figure that the orbital period of AD Andromeda is variable as expected. As shown in Fig. 1, the orbital period of AD Andromeda needs to be revised and the general trend of the $(O-C)_1$ curve shows a cyclic variation. Therefore, a sinusoidal term was added to a linear ephemeris to get a good fit to the $(O-C)_1$ curve (solid line in Fig. 1). Then, with means of a least-square method, the following equation was obtained:

$$\begin{aligned}\mathrm{Min.}I = {} & 2439002.5733(\pm 0.0015) \\ & + 0.^d98619240(\pm 0.00000014) \times E \\ & + 0.0186(\pm 0.0008)\sin[0.^\circ 0676 \times E \\ & + 14.^\circ 28(\pm 0.^\circ 04)].\end{aligned} \tag{2}$$

The derived period (P = 0.98619240 day) in the linear ephemeris is smaller than that (P = 0.986197 day) determined by Whitney (1957) and (P = 0.9861958 day) by Ruciński (1966), which can be used to predict the future times of light minimum. The sinusoidal term in Eq. (2) suggests a periodic variation with an amplitude of 0.0186 d. By using $\omega = 360^\circ P_e/T$, the period of $T = 14.38$ years of this periodic oscillation is determined. The residuals computed from Eq. (2) are given in the lower panel of Fig. 1 and are listed in the eighth column of Table 2. Such periodic oscillation can be usually explained either by the solar-like magnetic activity cycle mechanism (e.g., Applegate, 1992), or by the light travel-time effect via the presence of a tertiary companion (e.g., Borkovits and Hegedüs, 1996). The solar-like magnetic activity cycle mechanism was frequently used to explained the orbital period modulation of close binary stars containing at least one cool component (e.g., Hall, 1991; Qian et al., 1999, 2000). Given that the component star in AD Andromeda are both A0V type (Hill et al., 1975), we think that the mechanism of Applegate is inadequate to interpret the periodic oscillation.

Since the periodic oscillation can not be interpreted by the mechanism of Applegate, a simplest explanation of the cyclic period changes is the light travel-time effect via the presence of a tertiary companion (e.g., Borkovits and Hegedüs, 1996). The $(O-C)_2$ values were calculated with the linear ephemeris of Eq. (2) and are shown in the seventh column of Table 2 and displayed in Fig. 2. By considering an elliptical orbit of tertiary companion, the following equation:

$$(O-C)_2 = a_0 + \sum_{i=1}^{2}[a_i\cos(i\Omega E) + b_i\sin(i\Omega E)], \tag{3}$$

was used to determine the $(O-C)_2$ residuals. The results were obtained (solid line in Fig. 2.) and are listed in Table 3. by using the same value of Ω as that used in Eq. (2). The orbital parameters of the tertiary companion were computed with the formulae given by Kopal (1959),

$$a'_{12}\sin i' = c\sqrt{a_1^2 + b_1^2}, \tag{4}$$

$$e' = 2\sqrt{\frac{a_2^2 + b_2^2}{a_1^2 + b_1^2}}, \tag{5}$$

$$\omega' = \arctan\frac{(b_1^2 - a_1^2)b_2 + 2a_1a_2b_1}{(a_1^2 - b_1^2)a_2 + 2a_1b_1b_2}, \tag{6}$$

$$\tau' = t_0 - \frac{T}{2\pi}\arctan\frac{a_1b_2 - b_1a_2}{a_1a_2 + b_1b_2}, \tag{7}$$

where c is the speed of light, a'_{12}, i', e', ω', and τ' are the semi-major axis between the binary star and the center of mass with respect to the third companion, the orbital inclination of the third companion, the eccentricity of the third companion, the longitude of the periastron from the ascending node, and the time of the periastron passage, respectively. The results are listed in Table 3. Then, a calculation with the following well-known equation:

$$f(m) = \frac{4\pi^2}{GT^2} \times (a'_{12}\sin i')^3, \tag{8}$$

give a mass function of $f(m) = 0.16(\pm 0.02)\ M_\odot$ for the third companion. Where G is the gravitational constant, T is the period of the O–C oscillation. If we take the value of $M_1 = M_2 = 2.0M_\odot$ for an A0V star , the masses and the radii of the third companion for several different values of i' were calculated by using the following equation:

$$f(m) = \frac{(M_3\sin i')^3}{(M_1 + M_2 + M_3)^2}, \tag{9}$$

where M_1, M_2, and M_3 are the masses of the eclipsing pair and the third companion, respectively. The corresponding results are listed in Table 3.

4. Photometric solution for AD Andromeda

The first photoelectric light curve of AD Andromeda was obtained by Ruciński (1966), then undetermined photometric elements of AD Andromeda have derived by Ruciński (1966) and Giuricin and Mardirossian (1981). To check their results and get more accurate values, we now reanalyze this light curve using

Table 2
Photoelectric and CCD times of light minimum for AD Andromeda

JD.Hel.	Error (day)	Method	Minimum	E	$(O-C)_1$	$(O-C)_2$	Residuals	References
2400000+								
38999.4944	0.0013	Pe	I	−3	+0.0085	−0.0044	+0.0001	1
39002.4519	0.0006	Pe	I	0	+0.0074	−0.0055	−0.0009	1
39008.3682	0.0007	Pe	I	6	+0.0065	−0.0064	−0.0016	1
39029.5714	0.0007	Pe	II	27.5	+0.0066	−0.0062	−0.00104	1
39035.4900	0.0006	Pe	II	33.5	+0.0080	−0.0048	+0.0005	1
48499.5035		Pe	I	9630	+0.0066	+0.0133	−0.0019	2
50026.6027	0.0003	CCD	II	11178.5	−0.0162	−0.0064	+0.0078	3
50026.6034	0.0010	CCD	II	11178.5	−0.0155	−0.0057	+0.0085	3
50748.4820	0.005	CCD	II	11910.5	−0.0313	−0.0200	−0.0017	4
51095.6217	0.0002	CCD	II	12262.5	−0.0320	−0.0200	−0.0045	5
51099.5669	0.0008	CCD	II	12266.5	−0.0316	−0.0196	−0.0041	5
51338.2286		CCD	II	12508.5	−0.0289	−0.0164	−0.0045	6
51426.4953		CCD	I	12598	−0.0266	−0.0139	−0.0035	7
51426.4966	0.0007	CCD	I	12598	−0.0253	−0.0126	−0.0022	7
51488.6216	0.0011	CCD	I	12661	−0.0306	−0.0178	−0.0086	5
51813.5869	0.0002	CCD	II	12990.5	−0.0163	−0.0028	−0.0004	5
51832.8174	0.00007	CCD	I	13010	−0.0166	−0.0031	−0.0011	8
52135.5900	0.005	CCD	I	13317	−0.0057	+0.0084	+0.0037	10
52169.6114	0.0002	CCD	II	13351.5	−0.0080	+0.0062	+0.0008	5
52209.5536	0.0001	CCD	I	13392	−0.0067	+0.0076	+0.0013	5
52224.3463	0.0006	CCD	I	13407	−0.0069	+0.0074	+0.0008	11
52239.6333	0.0002	CCD	II	13422.5	−0.0059	+0.0084	+0.0016	5
52245.5511	0.0004	CCD	II	13428.5	−0.0053	+0.0091	+0.0020	5
52282.5341	0.0002	CCD	I	13466	−0.0046	+0.0098	+0.0021	5
52505.4228	0.0009	CCD	I	13692	+0.0042	+0.0191	+0.0071	12
52517.7443	0.0005	CCD	II	13704.5	−0.0018	+0.0131	+0.0010	5
52535.9919		CCD	I	13723	+0.0012	+0.0162	+0.0037	13
52633.6243	0.0003	CCD	I	13822	+0.0004	+0.0156	+0.0016	9
52637.5654	0.0009	CCD	I	13826	−0.0033	+.0119	−0.0022	5
52857.4894	0.0004	CCD	I	14049	−0.0006	+0.0150	−0.0017	14
52860.45033		CCD	I	14052	+0.0017	+0.0173	+0.0006	15
52869.3267	0.0001	CCD	I	14061	+0.0023	+0.0179	+0.0011	16
2400000+								
52897.4331	0.00007	CCD	II	14089.5	+0.0022	+0.0179	+0.0008	16
52923.5681	0.0004	CCD	I	14116	+0.0030	+0.0187	+0.0014	5
52930.4716	0.0005	CCD	I	14123	+0.0032	+0.0190	+0.0016	14
52950.6879	0.0002	CCD	II	14143.5	+0.0025	+0.0183	+0.0008	17
53201.6737	0.0004	CCD	I	14398	+0.0018	+0.0181	−0.0004	5
53298.3180	0.0002	CCD	I	14496	−0.0010	+0.0155	−0.0030	18
53653.3470	0.001	CCD	I	14856	−0.0020	+0.0153	−0.0011	19
53654.3310		CCD	I	14857	−0.0041	+0.0132	−0.0031	20
53654.33459	0.0031	CCD	I	14857	−0.0006	+0.0167	+0.0004	15
53763.3051	0.0040	CCD	II	14967.5	−0.0045	+0.0130	−0.0020	15
53763.3058	0.0038	CCD	II	14967.5	−0.0038	+0.0137	−0.0013	15
53763.3058	0.0041	CCD	II	14967.5	−0.0038	+0.0137	−0.0013	15
53763.3058	0.0040	CCD	II	14967.5	−0.0038	+0.0137	−0.0013	15
53764.2922	0.0005	CCD	II	14968.5	−0.0036	+0.0139	−0.0011	15
54026.6176	0.0042	Pe	II	15234.5	−0.0059	+0.0121	+0.0013	21
54039.43513		CCD	II	15247.5	−0.0089	+0.0091	−0.0015	15
54458.0635	0.0002	CCD	I	15672	−0.0201	−0.0012	−0.0032	22

[1] Ruciński (1966).
[2] Hübscher et al. (1992).
[3] Baldwin and Samolyk (1996).
[4] Paschke Anton (1998).
[5] Baldwin (2004).
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[8] Nelson (2001).
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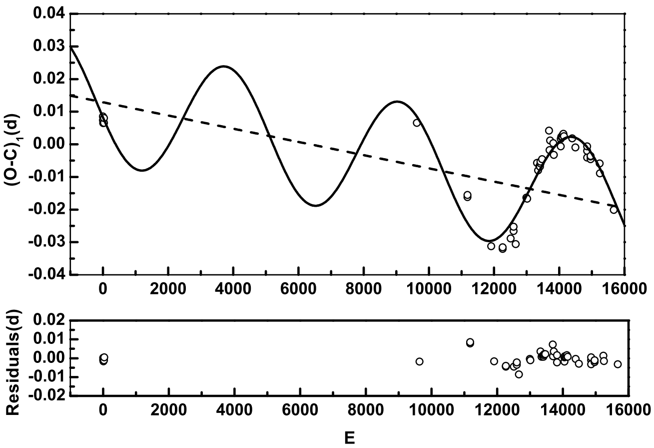

Fig. 1. $(O-C)_1$ diagram of AD Andromeda according to the linear ephemeris of Eq. (1) based on all available photoelectric and CCD times of light minimum. The solid line refers to a combination of a linear ephemeris and a cyclic period variation, and the dashed line to a new linear ephemeris. The residuals from the whole effect are displayed in the lower panel.

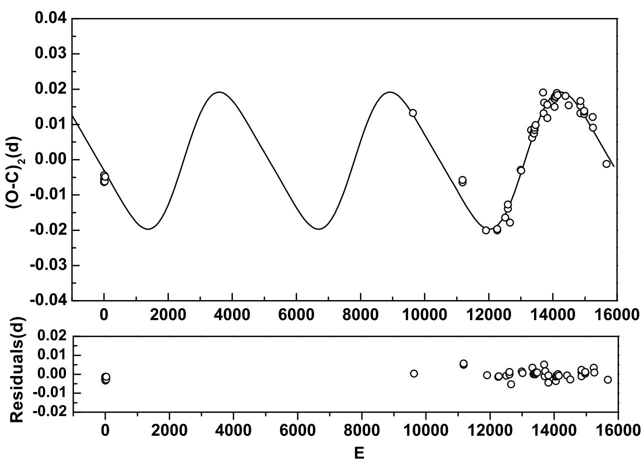

Fig. 2. $(O-C)_2$ diagram of AD Andromeda calculated with the linear ephemeris of Eq. (2) based on all available photoelectric and CCD times of light minimum. The solid line refers to a theoretical orbit of the assuming tertiary companion in an elliptical orbit in the system. The corresponding residuals are shown in the lower panel.

Table 3
Orbital parameters of the tertiary component star in AD Andromeda

Parameters	Values	Errors
a_0	-0.00025	±0.00025
a_1	-0.00396	±0.00098
b_1	-0.01828	±0.00065
a_2	+0.00118	±0.00098
b_2	+0.00251	±0.00244
$a'_{12}\sin i'$ (AU)	3.24	±0.12
e'	0.30	±0.24
ω'	$-89.°3$	±49.°7
τ' (Days)	38813	±414
$f(m)(M_\odot)$	1.6×10^{-1}	0.2×10^{-1}
$m_3(i'=90°)(M_\odot)$	1.76	±0.08
$m_3(i'=70°)(M_\odot)$	1.91	±0.09
$m_3(i'=50°)(M_\odot)$	2.49	±0.12
$m_3(i'=30°)(M_\odot)$	4.60	±0.26
$m_3(i'=10°)(M_\odot)$	38.33	±3.46
$A_3(i'=90°)$ (AU)	7.4	±0.4
$A_3(i'=70°)$ (AU)	7.2	±0.4
$A_3(i'=50°)$ (AU)	6.8	±0.4
$A_3(i'=30°)$ (AU)	5.6	±0.4
$A_3(i'=10°)$ (AU)	1.9	±0.2

Table 4
Photometric solutions for AD Andromeda

Parameters	Without l_3	With l_3
g_1	1.0	1.0
g_2	1.0	1.0
A_1	1.0	1.0
A_2	1.0	1.0
x_{1bol}	0.525	0.525
x_{2bol}	0.525	0.525
y_{1bol}	0.172	0.172
y_{2bol}	0.172	0.172
x_{1V}	-0.013	-0.013
x_{2V}	-0.013	-0.013
y_{1V}	0.722	0.722
y_{2V}	0.722	0.722
$i(°)$	82.322 (154)	82.634 (1.102)
$T_1(K)$	9790 (assumed)	9790 (assumed)
$T_2(K)$	9687 (60)	9688 (50)
q	1.000 (22)	0.988 (34)
Ω_1	4.1625 (605)	4.1137 (569)
Ω_2	4.3637 (957)	4.3521 (1134)
$L_{1V}/(L_{1V}+L_{2V})$	0.5387 (16)	
$L_{1V}/(L_{1V}+L_{2V}+L_{3V})$		0.55 (1)
$L_{3V}/(L_{1V}+L_{2V}+L_{3V})$		0.001 (4)
$r_1(pole)$	0.312 (6)	0.315 (6)
$r_1(side)$	0.322 (7)	0.326 (7)
$r_1(back)$	0.337 (9)	0.342 (9)
$r_2(pole)$	0.294 (8)	0.29 (1)
$r_2(side)$	0.302 (9)	0.30 (1)
$r_1(back)$	0.31 (1)	0.31 (1)
$\sum\omega_i(O-C)_i^2$	0.00886	0.00889

the 2003 version of the W–D program (Wilson and Devinney, 1971; Wilson, 1990, 1994; Wilson and Van Hamme, 2003). Given the A0V spectral type of AD Andromeda, we assumed an effective temperature of $T_1 = 9790K$ for the star 1 (star eclipsed at primary light minimum). The gravity-darkening coefficient, $g_1 = g_2 = 1.0$, and the bolometric albedo, $A_1 = A_2 = 1.0$, were adopted, which correspond to both radiative primary and secondary component. Bolometric and bandpass square-root limb-darkening coefficients were taken from Van Hamme (1993) and are listed in Table 4. The adjustable parameters were: the orbital inclination, i; the mean temperature of star 2, T_2; the monochromatic luminosity of star 1, L_{1v} and the dimensionless potentials of star 1 and 2, Ω_1 and Ω_2.

Giuricin and Mardirossian (1981) found the mass ratio to be 1.0, to check this value, a q-search method with the 2003 version of the W–D program (Wilson and Devinney, 1971; Wilson, 1990, 1994; Wilson and Van Hamme, 2003) was used (calculated around 1.0 for $q = 0.9, 0.95, 0.96, 0.98, 0.99, 1.0, 1.1, 1.2$). We found it is a detached binary star and the best mass ratio was $q = 1.0$, which agrees very well with the value of Giuricin and Mardirossian (1981). The photometric solutions are listed in Table 4. Meanwhile, we calculated a solution with third light (i.e. we made l_3 an adjustable parameter), the results are listed in column 3 of Table 4.

5. Discussions and conclusions

Based on all available photoelectric and CCD times of light minimum, a cyclic period change of AD Andromeda was discovered. The orbital period shows a periodic oscillation with a period of 14.38 years and an amplitude of 0.0186 days. Compared with the results estimated by Frieboes-Conde and Herczeg (1973), our results are more reliable because we adopted more accurate photoelectric and CCD data rather than visual and photographic ones. Based on the previous analysis, we think such periodic oscillation can not be explained by the mechanism of Applegate but by the light-time effect via the presence of a tertiary companion. It is shown that the eccentricity of the tertiary companion is small $e' = 0.30(\pm 0.24)$ indicating a nearly circular orbit of the companion. Based on our analysis, it is shown that the mass function of $f(m) = 0.16(\pm 0.02)M_\odot$. The mass of the third body is no less than $1.76(\pm 0.08)\ M_\odot$ and the separation between the binary and the tertiary companion is shorter than 7.4 AU.

The results of photoelectric light curve analysis are different from those obtained by Giuricin and Mardirossian (1981). Our computation shows that AD Andromeda is a detached binary star and inclination angle $i = 82.^\circ 322(\pm 0.^\circ 154)$. According to the relation of $L \sim M^{4.4}$, the contribution of the tertiary companion, if it is a single 1.76 solar mass main-sequence star, to the light of the system in the V band would then be roughly 22%. This is much larger than the value derived from the calculation of the third light $L_{3V}/(L_{1V} + L_{2V} + L_{3V}) \sim 0.001(\pm 0.004)$. Within the five times the standard error limit this will allow at most a few per cent of third light in the system. The low luminosity of the third component may be explained in two possible ways, either: (1) like the inner binary, the third component might itself be a close double star consisting of two stars of 0.88 solar mass, or (2) it is a dark star such as a neutron star.

Since many multiple systems are observed in nature, even among the brightest stars of the sky, e.g. Castor and Mizar (both sixfold systems), the first possibility is a quite likely one. With the above mass-luminosity relation and taking into account color corrections, two 0.88 solar mass stars will contribute not more than a few per cent to the total V-luminosity of the system.

On the other hand, the possibility of a neutron star companion has several problems. First of all, since neutron stars originate from stars more massive than 8 solar mass, one would expect that more than half the initial system mass was ejected in the supernova explosion. In that case the orbit of the third star would have become hyperbolic and the system would have been disrupted (Blaauw, 1961). Furthermore, 1.76 solar mass is more massive than any neutron star mass accurately measured so far in binary pulsar systems, which are always in the range 1.1–1.45 solar mass (e.g. see Stairs, 2004). Finally, one would expect the surfaces of the two A0V stars of the inner binary system to have been polluted with heavy elements produced in the supernova explosion, but there is as yet no evidence for this.

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