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THE THREE-DIMENSIONAL ORBIT AND PHYSICAL PARAMETERS OF 47 OPH

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ABSTRACT

Although 47 Oph has been shown to be a binary with a period of ~27 days using both spectroscopic and interferometric techniques, only a preliminary orbit has been obtained in the previous work due to the shortage of high precision measurements. Since 1997, new spectroscopic and interferometric measurements have been obtained with much higher precision by the spectrograph of the 2.16 m telescope at Xinglong station and the Navy Precision Optical Interferometer, respectively. Combining all of the measurements, a three-dimensional orbit is obtained with high precision in this work. Thus, the component masses are calculated to be 1.50 ± 0.06 and $1.34 \pm 0.06\,M_\odot$, respectively. The orbital parallax is 32.6 ± 0.6 mas, which is consistent with the *Hipparcos* parallax. With the known apparent magnitudes and color indices of the components, the derived luminosities are 7.80 ± 0.36 and $3.41 \pm 0.25\,L_\odot$. The estimated radii of the components are 2.06 ± 0.07 and $1.36 \pm 0.06\,R_\odot$. Finally, the evolutionary status of the components are investigated with the help of a stellar evolution model.

Key words: astrometry – binaries: spectroscopic – stars: fundamental parameters – stars: individual (47 Oph)

1. INTRODUCTION

The combination of optical long baseline interferometer and radial velocity (RV) measurements can describe the three-dimensional orbital motion of a binary, and consequently determine the component masses and orbital parallax. Given the high angular resolution of long baseline interferometers, 210 double-lined spectroscopic binaries (SB2s) with $(a_1 + a_2)$ $\sin i \geqslant 400\,\mu$as (where a_1, a_2 are the angular semimajor axes of orbits of the components relative to the system barycenter and i is the orbital inclination) were chosen from the Eighth Catalog of the Orbital Elements of Spectroscopic Binary Systems (Batten et al. 1989) as the observable sample for long baseline interferometers (Armstrong 1997). Among these systems, the astrometric orbits of 26 SB2s have been determined using the data observed with the Mark III Stellar Interferometer on Mt. Wilson until late 1992 (e.g., Armstrong et al. 1992; Pan et al. 1992; Hummel et al. 1995). The masses and absolute luminosities of the components have been compared with stellar evolution models (Hummel 1997).

The binary 47 Oph (HR 6493, HIP 85365, HD 157950) belongs to the abovementioned 210 SB2s and the combined spectral type of the system is F3V (Abt 2009). Only a preliminary orbit had been available until 1997 (Hummel 1997). There are two main reasons. On one hand, only six measurements have been observed by Mark III until 1997. On the other hand, the RV measurements were inadequate and not very accurate. Specifically, variable RVs of 47 Oph were detected by Campbell as early as 1907 (Campbell & Moore 1907). Spectroscopic orbits of the system with an orbital period of about 27 days were given later (Parker 1915; Abt & Levy 1976), but it should be mentioned that the precision of these historical RV data was low relative to the current RV measurements. In addition, when the direction of motion of the two components is nearly parallel to the tangent plane of the celestial sphere, the RV of the components cannot be separated effectively and were mistaken for the RV of the primary. Many measurements supplied by Abt & Levy (1976) were obtained during these times.

In order to improve the interferometric measurements of 47 Oph, 16 new measurements have been taken by the Navy Precision Optical Interferometer (NPOI) since 1997. New RV data with high precision were needed to determine the orbital solutions accurately. For this work, high-resolution spectra have been obtained by the coudé echelle spectrometer (CES) and High Resolution Spectrograph (HRS) mounted on the 2.16 m telescope at Xinglong station, and the two-dimensional correlation method (Zucker & Mazeh 1994) has been used to extract the RVs of the two components. On the basis of all the measurements mentioned above, we are now able to provide an accurate three-dimensional orbit of 47 Oph.

2. OBSERVATIONS

2.1. Mark III Observations and Data Reduction

The Mark III Stellar Interferometer (Shao et al. 1988) was operated on Mt. Wilson from 1990 to 1992. 47 Oph was observed during six nights on a baseline between the north D and south F stations (27 m), recording fringes in three narrowband channels (≈25 nm) centered at 500, 550, and 800 nm. The data were reduced as described by Mozurkewich et al. (1991), and the binary separation and position angle were fit to the data of each night. The uncertainty ellipse for the relative astrometric position is derived from the size of the central part of the synthesized point-spread function. The results are given in Table 1. The columns represent the date, the fractional Julian year of the observation, the number of measured visibilities, the derived separation (ρ) and position angle (θ), the axes and position angle of the uncertainty ellipse ($\sigma_{\rm maj}$, $\sigma_{\rm min}$, φ), and the deviation of the fitted relative binary position (ρ, θ) from the model values, respectively.

2.2. NPOI Observations and Data Reduction

The NPOI data were recorded between 1997 and 2002, first with the three-beam combiner and then, starting in 2002, with the six-beam combiner (Armstrong et al. 1998). The observations alternated between the science target and a calibrator. The

Table 1
Observation and Result Log for 47 Oph

UT Date (1)	Julian Year (2)	Number of Visibilities (3)	ρ (mas) (4)	θ (deg) (5)	σ_{maj} (mas) (6)	σ_{min} (mas) (7)	ϕ (deg) (8)	$O–C_\rho$ (mas) (9)	$O–C_\theta$ (deg) (10)
Jul 29	1990.573	21	3.95	289.51	1.41	0.20	77.9	−0.44	7.6
Aug 28	1990.655	15	4.81	71.87	1.96	0.20	75.7	1.75	13.4
Aug 09	1991.602	15	9.37	114.08	3.46	0.19	69.7	0.01	−0.5
Jun 28	1992.489	48	9.89	144.51	1.13	0.19	94.7	0.08	0.7
Jun 30	1992.495	36	8.44	153.90	0.88	0.20	89.5	0.30	0.1
Aug 01	1992.583	26	4.29	244.45	1.45	0.20	79.9	0.53	3.0
May 15	1997.369	510	11.36	129.24	1.02	0.15	177.5	0.03	1.0
May 26	2001.399	362	11.21	130.18	0.78	0.11	166.5	−0.14	0.1
May 27	2001.401	324	11.27	133.28	0.87	0.10	165.2	0.08	0.4
Jun 01	2001.415	342	8.21	150.92	0.80	0.11	165.7	−0.10	−1.8
Jun 08	2001.434	604	3.70	267.54	0.85	0.10	166.0	−0.50	−2.4
Jun 09	2001.437	805	3.86	290.06	0.98	0.17	178.2	−0.54	−1.2
Jun 10	2001.440	374	3.96	320.06	0.81	0.11	165.7	−0.00	7.1
Jun 15	2001.453	166	7.23	97.99	0.92	0.20	1.9	−0.11	−6.9
Jun 17	2001.459	845	9.57	116.48	1.02	0.16	177.0	−0.09	0.7
Jun 20	2001.467	1169	11.32	127.68	0.94	0.17	177.3	0.15	1.4
Jun 27	2001.486	586	8.63	149.67	0.83	0.11	166.0	0.08	−1.6
Jun 28	2001.489	1127	8.14	155.57	0.77	0.12	164.9	0.52	−1.2
May 19	2002.379	794	2.98	14.12	0.54	0.20	171.9	0.44	5.0
May 20	2002.381	160	3.17	58.73	0.25	0.17	159.5	−0.09	−3.9
Jun 07	2002.431	1349	5.45	176.72	0.27	0.23	165.0	0.24	−4.3
Jun 08	2002.434	48	4.36	193.71	2.19	0.10	129.4	0.02	−5.1

Table 2
List of NPOI Calibrators Used. V^2_{min} is the Minimum Estimated Calibrator Visibility Based on the Diameter θ_{V-K}

HD	Type	V	$V–K$	$E(B–V)$	θ_{V-K}	V^2_{min}	Nights
HD 886	B2IV	2.83	−0.940	0.010	0.498	0.96	3
HD 23338	B6V	4.30	−0.202	0.040	0.388	0.98	1
HD 87737	A0Ib	3.49	0.191	−0.020	0.753	0.94	2
HD 89021	A2IV	3.40	−0.018	0.030	0.708	0.95	3
HD 91312	A7IV	4.80	0.603	−0.040	0.541	0.96	5
HD 95128	G0V	5.10	1.350	−0.020	0.749	0.94	2
HD 97633	A2V	3.34	0.258	−0.060	0.858	0.91	1
HD 108283	F0p,shell	5.00	0.851	0.220	0.574	0.95	3
HD 117176	G5V	5.00	1.500	0.010	0.976	0.87	2
HD 120136	F6IV	4.50	0.993	0.018	0.849	0.89	2
HD 128167	F3Vvw	4.46	1.124	−0.020	0.756	0.91	11
HD 134083	F5V	4.93	1.067	−0.010	0.654	0.93	3
HD 135742	B8V	2.61	−0.295	0.000	0.838	0.97	1
HD 141003	A2IV	3.67	0.124	0.010	0.676	0.93	2
HD 143894	A3V	4.80	0.181	0.020	0.417	0.97	2
HD 147394	B5IV	3.89	−0.395	0.020	0.439	0.97	2
HD 147547	A9III	3.75	0.806	−0.006	0.944	0.86	3
HD 156164	A3IV	3.14	0.332	0.000	0.987	0.86	3
HD 161868	A0V	3.75	0.128	0.060	0.650	0.93	16
HD 164353	B5Ib	3.97	−0.031	0.120	0.503	0.96	4
HD 176437	B9III	3.24	0.118	0.020	0.817	0.89	7
HD 177724	A0Vn	2.99	0.114	0.030	0.919	0.87	7
HD 177756	B9Vn	3.44	−0.124	−0.020	0.641	0.93	5
HD 192696	A3IV-Vn	4.30	0.222	0.030	0.536	0.95	3
HD 212593	B9Iab	4.56	0.277	0.120	0.462	0.97	1
HD 213558	A1V	3.77	−0.081	0.000	0.568	0.95	2
HD 213998	B9IV-Vn	4.02	−0.216	−0.020	0.462	0.97	1
HD 214923	B8.5 V	3.40	−0.166	0.003	0.635	0.94	3

latter are stars of sufficiently small angular diameters estimated using surface brightness relationships published by Mozurkewich et al. (2003) for the purpose of deriving the atmospheric and instrumental visibility degradation. Their relevant properties are given in Table 2.

Table 3 gives information on dates, configurations, and calibrator stars observed for each night. A configuration is given as a triple of stations (e.g., "AC-AE-W7," using astrometric stations Center and East, as well as imaging station W7) if data from all three involved baselines were used,

Table 3
NPOI Observation for 47 Oph

UT Date (1)	Julian Year (2)	Triangles and Baselines (3)	Calibrators (HD) (4)
1997 May 15	1997.3687	AC0-AE0-AW0	97633 161868
2001 May 26	2001.3988	AE0-AW0-W07	91312 87737 141003 161868 177724 128167
2001 May 27	2001.4016	AE0-AW0-W07	91312 87737 161868 177724 128167
2001 Jun 01	2001.4152	AE0-AW0-W07	161868 177724 128167
2001 Jun 08	2001.4342	AE0-AW0-W07	91312 161868 176437 128167 134083
2001 Jun 09	2001.4371	AC0-AE0-AW0	108283 161868 192696 213558 128167 134083
2001 Jun 10	2001.4399	AE0-AW0-W07	108283 161868 176437 128167 134083
2001 Jun 15	2001.4535	AC0-AE0-AW0	91312 143894 89021 120136 147547 161868 214923 95128 117176 128167
2001 Jun 17	2001.4589	AC0-AE0-AW0	91312 143894 89021 120136 147547 161868 95128 117176 128167
2001 Jun 20	2001.4671	AC0-AE0-AW0	108283 212593 147547 161868 213558 128167
2001 Jun 27	2001.4862	AE0-AW0-W07	161868 177756 128167
2001 Jun 28	2001.4889	AE0-AW0-W07	89021 161868 177756 128167
2002 May 19	2002.3789	AC0-AW0-E02 AE0-AW0-E02 E02-AN0	161868 176437
2002 May 20	2002.3816	AE0-AN0-AW0	161868 176437
2002 Jun 07	2002.4308	AC0-AW0-E02 AE0-AN0-AW0 AE0-AN0-E02 AE0-AW0-E02 AN0-AW0-E02	147394 161868 192696
2002 Jun 08	2002.4335	AE0-AW0 AN0-AW0	147394 161868 176437 192696
1990 Jul 29	1990.5729	AE0-AW0 AN0-AW0	886 135742 141003 156164 176437 177724 214923
1990 Aug 28	1990.6548	AE0-AW0 AN0-AW0	23338 886 176437 177724 214923
1991 Aug 09	1991.6024	AE0-AW0 AN0-AW0	886 164353 177756 213998
1992 Jun 28	1992.4894	AE0-AW0 AN0-AW0	156164 164353
1992 Jun 30	1992.4950	AE0-AW0 AN0-AW0	156164 164353 177724 177756
1992 Aug 01	1992.5824	AE0-AW0 AN0-AW0	164353 177724 177756

including the corresponding closure phase. If a single baseline is listed, squared visibility data from that baseline were used but no closure phase data were available involving this baseline.

We used a pipeline written in GDL[4] for the OYSTER[5] NPOI data reduction package, which follows the procedures described by Hummel et al. (1998, 2003).

2.3. Spectroscopic Observations and Data Reduction

To obtain precise RV measurements, high-resolution spectral observations of 47 Oph have been carried out since 2011. At the outset, the CES (Zhao & Li 2001) mounted on the 2.16 m telescope at Xinglong station was used. We chose the blue arm and medium focal length camera, a configuration covering a wavelength range of 3300–5800 Å with a spectral resolution ($R = \lambda/\Delta\lambda$) of about 80,000. After 2012 July, the HRS covering the wavelength region of 4030–10250 Å installed on the same telescope came into use. The slit width was set to 0.19 mm, corresponding to a spectral resolution of ~45,000 around 5500 Å.

The spectra were reduced and normalized to a continuum using IRAF.[6] RVs were measured using the two-dimensional correlation method (Zucker & Mazeh 1994) with synthetic spectral templates generated by the SPECTRUM spectral synthesis package (Gray & Corbally 1994); see also the web (http://phys.appstate.edu/~grayro/spectrum/spectrum.html) and the ATLAS9 model atmosphere grids (Kurucz 1993). Finally, we converted the topocentric velocities into the barycentric velocities with the IRAF tool BCVCORR. The zero-point offset of the observation equipment was determined to be -0.50 ± 0.21 km s^{-1} by measuring the RVs of the Geneva Radial-Velocity Standard Stars (Udry et al. 1999). All the RV data along with the historical RV data are corrected by this zero-point offset and listed in Table 4.

3. ORBIT DETERMINATION

The interferometric (t, ρ, θ) and RV (t, V) measurements are two complementary types of observations constraining the parameters (a'', e, i, ω, Ω, P, T) and (K_1, K_2, V_0, e, ω_A, P, T), respectively. The relation between ω and ω_A satisfies $\omega_A = \omega - 180°$. The interferometric data expressed as the separation of the two components (ρ), the position angle (θ) can be transferred to the rectangular coordinates

$$x = \rho \cos\theta,$$
$$y = \rho \sin\theta,$$

and the errors in the corresponding coordinates can be computed as

$$\sigma_x = \sqrt{\sigma_{\rm maj}^2 \cos^2\varphi + \sigma_{\rm min}^2 \sin^2\varphi},$$
$$\sigma_y = \sqrt{\sigma_{\rm maj}^2 \sin^2\varphi + \sigma_{\rm min}^2 \cos^2\varphi}.$$

The parameters ($\sigma_{\rm maj}$, $\sigma_{\rm min}$, φ) in the above expression are given in Table 1.

When we use the least square method to fit the orbit, a simultaneous adjustment of the fit to interferometric and spectroscopic data is used to derive the orbital solutions. The

4 http://gnudatalanguage.sourceforge.net
5 http://eso.org/~chummel/oyster/oyster.html
6 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 4
Radial-velocity Measurements of 47 Oph

JD 2400000	RV_p (km s^{-1})	σ_p (km s^{-1})	$O–C$ (km s^{-1})	RV_s (km s^{-1})	σ_s (km s^{-1})	$O–C$ (km s^{-1})	Reference
17414.795	28.8	5.4	0.0	−71.7	8.0	0.6	Parker (1915)
17424.714	−23.8	5.4	−1.2	−31.2	8.0	−3.5	Parker (1915)
18832.796	44.8	5.4	−8.7	−80.7	8.0	−10.9	Parker (1915)
18857.695	68.6	5.4	0.2	−71.8	8.0	0.8	Parker (1915)
18910.605	65.0	5.4	−4.1	−63.6	8.0	−9.5	Parker (1915)
19146.873	74.8	5.4	5.7	−65.1	8.0	6.5	Parker (1915)
19147.856	61.9	5.4	2.4	−46.6	8.0	4.8	Parker (1915)
19173.849	66.1	5.4	1.3	−64.4	8.0	3.6	Parker (1915)
19224.633	62.6	5.4	5.2	−56.9	8.0	5.4	Parker (1915)
19225.660	80.3	5.4	11.4	−71.8	8.0	−16.0	Parker (1915)
19250.575	46.8	5.4	−5.5	−58.9	8.0	14.0	Parker (1915)
19278.574	65.0	5.4	−3.7	−80.1	8.0	−7.3	Parker (1915)
19302.522	25.7	5.4	−17.3	−82.6	8.0	−19.8	Parker (1915)
19306.515	43.4	5.4	11.1	−81.8	8.0	−13.6	Parker (1915)
19329.500	52.7	5.4	−1.1	−57.2	8.0	−1.7	Parker (1915)
19487.902	73.0	5.4	8.4	30.0	8.0	−0.1	Parker (1915)
19513.833	52.9	5.4	−7.1	−58.1	8.0	14.9	Parker (1915)
19566.773	73.0	5.4	7.9	−50.7	8.0	9.2	Parker (1915)
19567.742	64.6	5.4	−3.2	−76.9	8.0	−3.8	Parker (1915)
19644.557	51.8	5.4	1.9	−27.6	8.0	4.0	Parker (1915)
19935.743	81.6	5.4	15.4	−61.9	8.0	−18.2	Parker (1915)
39277.920	−0.1[a]	0.8	3.1	…	…	…	Abt & Levy (1976)
39989.002	−1.6[a]	1.3	14.8	…	…	…	Abt & Levy (1976)
40051.659	0.9[a]	2.0	16.8	…	…	…	Abt & Levy (1976)
40373.894	10.1[a]	1.2	−12.0	…	…	…	Abt & Levy (1976)
40432.675	11.0[a]	1.1	−8.5	…	…	…	Abt & Levy (1976)
40433.699	1.4[a]	0.5	0.1	…	…	…	Abt & Levy (1976)
40697.929	−0.8[a]	1.4	12.5	…	…	…	Abt & Levy (1976)
40758.704	−20.6	1.5	0.3	24.5	1.6	−3.3	Abt & Levy (1976)
40759.821	−22.5	1.8	−3.9	17.8[a]	0.7	−8.03	Abt & Levy (1976)
41028.024	2.0[a]	0.7	1.2	…	…	…	Abt & Levy (1976)
41048.989	−9.9[a]	2.0	8.8	…	…	…	Abt & Levy (1976)
41085.856	55.7	0.4	0.2	−58.0	0.7	0.1	Abt & Levy (1976)
41086.885	69.1	0.9	0.9	−71.5	2.9	0.9	Abt & Levy (1976)
41102.766	−5.4[a]	1.8	10.3	…	…	…	Abt & Levy (1976)
41103.758	−0.4[a]	1.6	12.3	…	…	…	Abt & Levy (1976)
41201.676	−24.0	1.0	0.7	18.0[a]	2.8	−13.9	Abt & Levy (1976)
41202.724	−26.7	1.8	−2.4	17.6[a]	2.7	−14.0	Abt & Levy (1976)
41204.655	−24.8	3.2	−2.7	17.4[a]	3.2	−12.1	Abt & Levy (1976)
41233.615	−2.1[a]	0.6	15.0	…	…	…	Abt & Levy (1976)
41234.587	1.9[a]	1.0	16.3	…	…	…	Abt & Levy (1976)
55664.284	6.5	0.8	1.5	−23.3	0.6	1.6	The present work
55664.319	6.5	0.8	1.3	23.7	0.6	1.0	The present work
55664.343	6.5	0.9	1.1	−23.2	0.9	0.8	The present work
55666.245	19.6	1.5	−1.2	−4.5	0.7	−3.1	The present work
55666.276	19.9	1.5	−1.2	−5.0	0.7	−3.9	The present work
55666.300	21.1	2.6	−0.2	−3.7	0.5	−1.2	The present work
55666.335	20.7	1.3	−0.9	−3.7	0.6	−1.6	The present work
56051.265	−19.2	1.7	1.8	−18.0	1.0	2.4	The present work
56120.095	−3.1	0.8	−4.5	−5.5	0.9	−4.9	The present work
56434.232	28.8	1.6	3.3	−15.6	1.5	4.2	The present work
56434.241	28.1	1.9	2.8	−16.8	1.3	3.3	The present work
56434.274	27.8	1.9	3.4	−4.0	0.8	−0.7	The present work
56435.219	3.8	1.6	−0.5	−4.2	0.8	−1.3	The present work
56435.231	4.5	1.0	0.4	27.8	0.7	0.3	The present work
56435.258	4.3	1.3	0.6	−24.7	0.5	0.5	The present work
56445.265	−17.4	0.9	3.9	−3.8	0.7	−1.0	The present work
56445.282	−19.0	0.9	2.2	−17.7	1.6	3.1	The present work
56445.303	−18.1	0.9	3.1	5.7	1.0	3.7	The present work
56447.204	−17.9	1.3	−0.8	−3.8	0.5	−1.4	The present work
56447.219	−16.4	1.0	0.6	23.2	0.7	0.6	The present work

Table 4
(Continued)

JD 2400000	RV_p (km s^{-1})	σ_p (km s^{-1})	$O–C$ (km s^{-1})	RV_s (km s^{-1})	σ_s (km s^{-1})	$O–C$ (km s^{-1})	Reference
56794.226	6.2	1.1	0.5	27.9	0.5	0.5	The present work
56794.236	6.1	0.8	0.4	27.9	0.5	0.5	The present work
56794.296	6.1	1.0	0.0	27.4	0.5	0.3	The present work

[a] The RV data are not used to fit the orbit.

objective function can be written as

$$\chi^2 = \sum_{i=1}^{N_1}\left[\left(\frac{x_{o,i} - x_i}{\sigma_{x,i}}\right)^2 + \left(\frac{y_{o,i} - y_i}{\sigma_{y,i}}\right)^2\right] + \sum_{j=1}^{N_2}\left(\frac{V_{po,j} - V_{p,j}}{\sigma_{vp,j}}\right)^2 + \sum_{k=1}^{N_3}\left(\frac{V_{so,k} - V_{s,k}}{\sigma_{vs,k}}\right)^2. \quad (1)$$

N_1, N_2, and N_3 represent the number of interferometric measurements, the primary RV data, and the secondary RV data. The subscript o represents the observation and the subscripts p, s represent the primary and the secondary, respectively. The computed parameters x, y, V_p, and V_s are a function of the orbital solutions, and readers can refer to Pourbaix (1998) for more information.

Considering that the zero points of the RV measurements with different equipments may be inconsistent, zero-point adjustments should be made when combining the historical RV and ours. When we fit the orbit by combing all the historical RV data and our new ones, the offsets are fitted as parameters in function (1). Including two zero-point offset parameters, there are 12 parameters that need to be adjusted together.

As Equation (1) shows, each measurement is weighted by the inverse square of its own error. However, no errors were given for the RV data published by Parker (1915), but proper errors are needed to properly weight the data. Therefore, we use first all the RV data with the same weights to fit the RV curve. Assuming that the fitted curve is true for this system, we can estimate the errors σ of the RV measurements for the primary and secondary considering the mathematical expectation of the absolute value of the residuals:

$$\sigma_p = \sum_{i=1}^{N_p}\frac{\left|V_{po,i} - V_{p,i}\right|}{N_p}, \quad (2)$$

$$\sigma_s = \sum_{i=1}^{N_s}\frac{V_{so,i} - V_{s,i}\big|}{N_s}. \quad (3)$$

According to the above computation, we assign an error of 5.4 km s^{-1} to the RV measurements of the primary, and 8.0 km s^{-1} to that of the secondary for the RV data from Parker (1915). At the same time, as mentioned in the Introduction, in the early days it was difficult to efficiently distinguish the component RVs when they were close to each other. Thus, we have not used the data if there is only a primary RV or the residual of the RV is larger than 8 km s^{-1}. For these data, though they are distinguished from the primary RV, there are large deviations.

The method of Levenberg–Marquardt is used to find the global minimum for the objective function (1) where 12 parameters are obtained. Among them, offsets of 0.55 ± 1.01 and 0.37 ± 0.38 km s^{-1} are derived for the historical RV data published by Parker (1915) and Abt & Levy (1976) relative to the barycenter, respectively. The orbital solution is shown in Table 5 together with the orbital parallax and the component masses. In Table 5, the historical orbital solutions (Parker 1915; Hummel 1997) are also listed for comparison. From this table, it can be seen that the orbital parallax is 32.6 ± 0.6 mas, which is consistent with the *Hipparcos* parallax of 33.25 ± 0.25 mas (van Leeuwen 2007). The long baseline interferometric measurements and the fitted apparent orbit are shown in Figure 1. The data with dot ellipses observed by Mark III have already published by Hummel (1997), and the data with solid ellipses are new data observed by the NPOI. From this figure, it can be seen that the present interferometric measurements have made great progress both in the accuracy and in the orbital coverage. The RV data and the fitted RV curve are shown in Figure 2. The black, green, and red symbols indicate the RV data supplied by Parker (1915), Abt & Levy (1976), and the 2.16 m telescope at Xinglong station, respectively. The blue symbols represent the RV data that were not used to fit the orbit. These rejected data all deviate from the theoretical predictions and our new data compensate for the shortage of the historical data very well.

Table 5
The New Derived and Historical Orbital Parameters and Masses of 47 Oph

Parameter	This Work	Parker (1915)	Hummel (1997)
V_0(km s^{-1})	1.67 ± 0.13	0.4	⋯
K_1(km s^{-1})	46.92 ± 0.40	47.5	⋯
K_2(km s^{-1})	52.80 ± 0.39	50.7	⋯
ω_A(deg)	27.04 ± 0.54	14.5	17 ± 4
e	0.481 ± 0.002	0.49	0.505 ± 0.009
P(days)	26.27565 ± 0.00004	26.2765	26.270 ± 0.003
T(JD 2400,000)	48103.380 ± 0.026	18411.524	48525
a(mas)	7.99 ± 0.10	⋯	7.9 ± 0.2
i(deg)	59.5 ± 1.3	⋯	54 ± 2
Ω(deg)	121.8 ± 1.0	⋯	121 ± 3
Orbital parallax(mas)	32.6 ± 0.6	⋯	⋯
$M_1(M_\odot)$	1.50 ± 0.06	⋯	⋯
$M_2(M_\odot)$	1.34 ± 0.06	⋯	⋯

4. DISCUSSION AND CONCLUSION

In the Catalog of Stellar Photometry in Johnson's 11 color system, the combined apparent magnitudes in the U, B, V, R, I, J, H, K bands are 4.90, 4.93, 4.54, 4.16, 3.95, 3.79, 3.45, 3.55

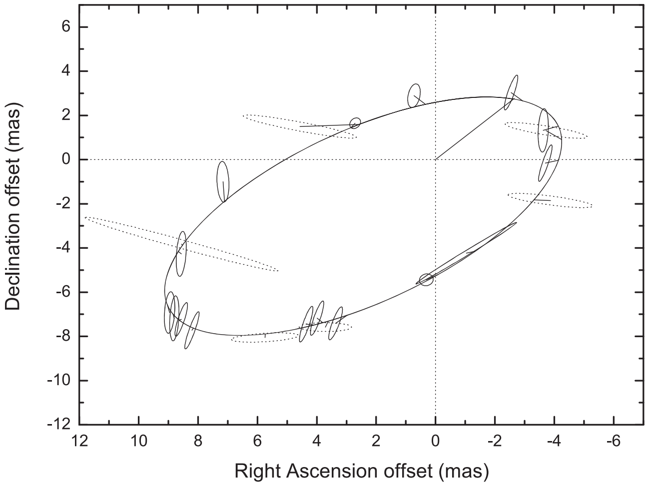

Figure 1. Apparent orbit and interferometric data of 47 Oph. The ellipses indicate the astrometric uncertainty. The data with dot ellipses observed by Mark III have already been published by Hummel (1997), and the data with solid ellipses are new data observed by the NPOI. The straight solid line indicates the periastron.

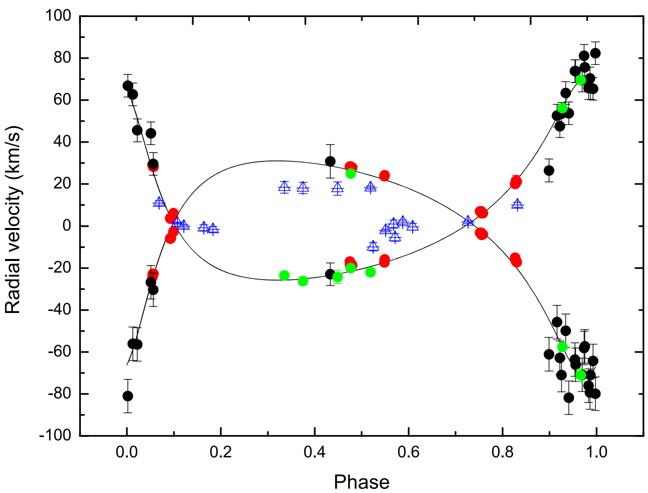

Figure 2. Radial-velocity curve and the observed RV data. The black, green, and red filled circles denote the RV data supplied by Parker (1915), Abt & Levy (1976), and measured in this work, respectively. The blue triangles represent the RV data that were not used to fit the orbit.

(Ducati 2002), respectively. The magnitude differences given by Mark III and NPOI between the two components are 1.1 ± 0.1, 0.9 ± 0.1, 0.9 ± 0.1 at 850, 700, 500 nm, respectively. Since the V band is centered at 550 nm, we can estimate the magnitude difference in the V band as 0.9 ± 0.1. With the combined apparent magnitude and magnitude difference, the apparent magnitude in the V band is calculated to be 4.93 ± 0.03 for the primary and 5.83 ± 0.07 for the secondary. Similarly, we can calculate the magnitudes in the R, I bands of the components as 4.34 ± 0.03, 4.28 ± 0.03 for the primary and 5.24 ± 0.07, 5.39 ± 0.07 for the secondary. From the same color index (V–R) of the two components, we can infer that the two components have very similar temperatures. The combined color index (B–V) for the system is 0.39, and the bolometric correction is 0.022 using tables from Flower (1996). The effective temperature of the system is 6726 ± 80 K

Table 6
Derived Physical Parameters of 47 Oph

Parameter	Primary	Secondary
m_V	4.93 ± 0.03	5.83 ± 0.07
$V - R$	0.38 ± 0.04	0.38 ± 0.10
$V - I$	0.65 ± 0.04	0.45 ± 0.10
BC	0.022 ± 0.005	0.022 ± 0.005
$L(L_\odot)$	7.80 ± 0.36	3.41 ± 0.25
$R(R_\odot)$	2.06 ± 0.07	1.36 ± 0.06

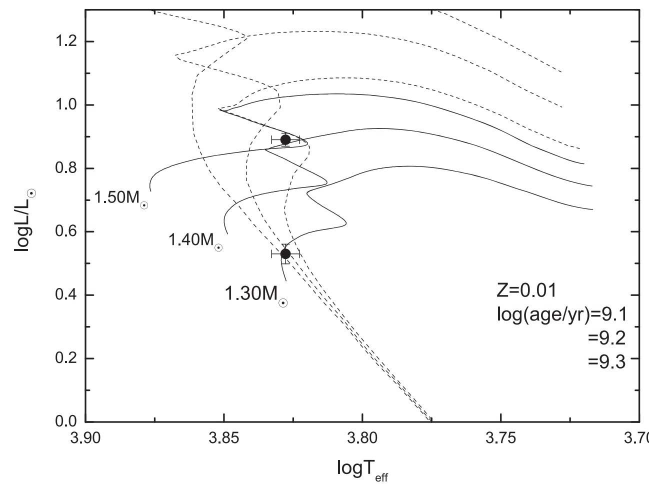

Figure 3. Evolutionary tracks for the component stars and isochrones of 47 Oph (Mowlavi et al. 2012). The solid lines and dashed lines indicate the mass tracks of 1.50, 1.40, 1.30 $M_\odot$ and the isochrones of $\log(\text{age yr}^{-1}) = 9.1$, 9.2, 9.3, respectively.

(Casagrande et al. 2011). Based on the orbital parallax 32.6 ± 0.6 mas and the bolometric correction, the luminosity is $7.80 \pm 0.36\, L_\odot$ for the primary and $3.41 \pm 0.25\, L_\odot$ for the secondary. Combined with the Stefan–Bolzmann's law, the radii of the primary and the secondary can be easily calculated as 2.06 ± 0.07 and $1.36 \pm 0.06\, R_\odot$. All the derived fundamental parameters for the components are listed in Table 6.

To investigate the evolutionary status of the two components of 47 Oph, we compared the ($\log T_{\text{eff}}$, $\log L/L_\odot$) values of the components with the evolutionary tracks given by Mowlavi et al. (2012) and find a good match with metallicity $Z = 0.01$. Figure 3 shows three tracks of mass = 1.5, 1.4, 1.3 $M_\odot$ in the ($\log T_{\text{eff}}$, $\log L/L_\odot$) plane. The isochrones for $\log(\text{age yr}^{-1}) = 9.1$, 9.2, 9.3 are shown in Figure 3. From this figure we can infer that the logarithm of the isochrone age of the system is between 9.2 and 9.3.

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