

## Parallax, mass, and orbit of the 9 Puppis binary system

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(Received 19 December 1974)

The parallax, orbit, and masses of the 9 Puppis binary system are redetermined. The weighted mean absolute parallax of all determinations is  $+0.062 \pm 0.003$  (standard error). This parallax, with the visual orbit determined by Douglass, indicates masses of  $0.86 \pm 0.17 M_{\odot}$  and  $0.99 \pm 0.19 M_{\odot}$  for the primary and secondary, respectively. These values fall within the scatter of the empirically determined mass-luminosity relationship.

### INTRODUCTION

THE duplicity of 9 Pup (BD  $-13^{\circ}2267$ , ADS 6420) was discovered by Burnham in 1873. Its combined visual magnitude ( $V$ ), color index ( $B-V$ ), and spectral type are 5.16, +0.60, and G1 V, respectively. The spectrum of the companion has not been resolved, although the visual magnitude difference is only 0.6.

Struve (1923) deduced a center-of-mass velocity of  $-17.8 \text{ km sec}^{-1}$  and a semiamplitude for the primary's radial velocity curve of  $3.52 \text{ km sec}^{-1}$ . Van de Kamp (1939) analyzed 63 Sproul plates and adopted a weighted mean absolute parallax of  $+0''.059$  and a visual photocentric semimajor axis of  $+0''.085$ . Combining this with a visual orbit by Woolley and Symms (1937), he derived masses of  $0.9 M_{\odot}$  for both components, which are in good agreement with the empirical mass-luminosity relation. However, on the basis of 67 Van Vleck plates, Grossenbacher and Mesrobian (1969) decided that the two components are somewhat over-luminous. They found a visual photocentric semimajor axis of  $+0''.111 \pm 0''.011$  (standard error) and adopted a weighted mean absolute parallax of  $+0''.063 \pm 0''.006$ . In their study of the mass-luminosity relation, Harris, Strand, and Worley (1963) also concluded from published values of the parallax, mass ratio, and orbital elements of 9 Puppis that both components are over-luminous. These investigators suggested that a faulty parallax was probably responsible.

In the following sections we shall reexamine the 9 Puppis binary system and redetermine the mass and luminosity of its solar-type components.

### I. DATA AND REDUCTIONS

The astrometric material for this study consists of 73 exposures on 31 plates obtained during the years 1947-1971 with the Allegheny Observatory 30-in. Thaw photographic refractor. The plates were measured on the Strand Automatic Measuring Machine (SAMM) at the United States Naval Observatory and their individual exposures reduced by the central overlap technique (Gatewood and Eichhorn 1973). All exposures were assigned unit weights. The initial positions and proper motions of the seven reference stars were obtained from a similar reduction of three early- and three late-epoch manually measured reference plates. The final positions and proper motions are in the system of the SAOC, ostensibly that of the FK4, as determined from eight stars common to that catalog and Table II.

Since the maximum separation of 9 Puppis is only  $0''.6$ , its images on our plates are blended and un-elongated. Orbital factors were computed on the basis of the visual orbit, by Geoffrey Douglass of the U. S. Naval Observatory, which is presented in Table I. The orbit was determined, utilizing visual observations through 1972, by differential corrections.

### II. RESULTS AND CONCLUSIONS

The iterations of the separate right ascension and declination solution converged on the star constants given in Table II, together with their standard errors. The star numbers are a continuing sequence with the most recent contribution being that by Gatewood and Russell (1974). Those stars listed without parallaxes were measured on reference plates only. The position angles ( $\theta$ ) and separations ( $\rho$ ) mentioned in the footnotes, as well as the positions and proper motions listed in Table II, refer to the equator and equinox of 1950.0. The photographic magnitudes are in the AGK3 system and were interpolated using measurements with the Allegheny Observatory Cuffey iris photometer. Their internal standard error is about  $0^m.1$ . The color indices were estimated from published photovisual magnitudes and from the spectral types of unreddened F and late-A stars. The reduced photographic magnitude of the image of 9 Puppis is equal to that of the average of the reference stars: 12.0. The relative parallaxes were corrected to absolute by adding  $+0''.0027$  in accordance

TABLE I. Orbital elements and Thiele-Innes constants for 9 Puppis.

Element	Value	Standard error
$P$	23.26	0.07
$T$	1915.96	0.13
$a$	$0''.616$	$0''.020$
$e$	0.752	0.018
$i$	$80^{\circ}79$	$0^{\circ}72$
$\omega$	$72^{\circ}65$	$0^{\circ}54$
$\Omega$	$103^{\circ}45$	$1^{\circ}08$
$A$	$-0''.1343$	$0''.0049$
$B$	$+0''.1568$	$0''.0060$
$F$	$+0''.1081$	$0''.0083$
$G$	$-0''.5787$	$0''.0209$

TABLE II. The positions, proper motions, and parallaxes of 25 stars in the region of 9 Puppis.

No.	Name	$m_{pg}$	C.I.	$\pi_{ab}$	$\sigma_{\pi}$	R.A. <sub>1950</sub>	$\sigma_{R.A.}$	$\mu_{\alpha}$	$\sigma_{\mu_{\alpha}}$	Dec <sub>1950</sub>	$\sigma_{Dec}$	$\mu_{\delta}$	$\sigma_{\mu_{\delta}}$
178	BD -13°2249	9.9	+1.3			7 <sup>h</sup> 47 <sup>m</sup> 30 <sup>s</sup> .3590	14	+0 <sup>o</sup> .00139	10	-13°45'11".731	26	-0 <sup>o</sup> .0292	18
179	BD -13°2250	9.1	+0.3			7 47 33.0849	33	-0.00087	23	-13 35 11.183	30	-0.0050	21
180	BD -13°2252	10.0	+0.2			7 47 41.6611	12	-0.00015	8	-13 52 17.525	36	-0.0044	26
181	BD -13°2251	9.8	+1.4			7 47 42.2636	34	-0.00120	24	-13 24 22.307	32	-0.0007	23
182	BD -13°2254	9.6	+0.3			7 48 02.4780	13	-0.00155	9	-13 27 50.726	36	+0.0003	25
183	BD -13°2255	9.7	+0.7			7 48 18.6795	19	-0.00419	14	-13 37 51.319	37	-0.0407	26
184	AC 1088 No. 1589	12.0		+0 <sup>o</sup> .0048	29	7 48 44.4776	2	-0.00108	2	-13 52 12.161	5	-0.0100	3
185	AC 1088 No. 1637	12.0		-0.0033	27	7 48 56.5287	2	-0.00138	2	-13 56 01.590	4	-0.0031	2
186	AC 1088 No. 1653	12.1		+0.0039	19	7 49 01.2626	2	-0.00234	1	-13 35 43.739	3	+0.0072	2
187	BD -13°2262	11.3	+0.8			7 49 05.6313	9	-0.00296	6	-13 27 51.621	58	+0.0126	41
188	BD -13°2264	10.5	+0.1			7 49 17.7390	20	-0.00109	14	-14 06 07.881	16	-0.0096	11
189 <sup>a</sup>	AC 1088 No. 1750	12.3				7 49 23.7649	12	-0.00147	8	-13 55 26.951	37	-0.0113	26
190 <sup>a</sup>	AC 1088 No. 1751	13.0				7 49 23.9289	54	-0.00088	38	-13 55 28.401	63	-0.0192	45
191	BD -13°2266	10.5	+0.2			7 49 24.5130	16	-0.00193	11	-13 56 45.745	18	+0.0027	13
192 <sup>b</sup>	9 Pup	5.8 <sup>b</sup>	+0.4	+0.0608	44	7 49 27.3080	4	-0.00622	3	-13 45 50.600	17	-0.3353	4
193	BD -13°2268	12.0	+0.5	+0.0072	38	7 49 05.6313	3	-0.00271	2	-13 46 01.342	07	+0.0064	4
194 <sup>c</sup>	AC 1088 No. 1851	12.9				7 49 55.5897	57	-0.00251	41	-14 03 40.986	35	+0.0066	25
195 <sup>c</sup>	AC 1088 No. 1852	12.1				7 49 55.7498	13	-0.00171	9	-14 03 42.861	32	+0.0001	23
196	vdK-Vys.42	12.1	+0.6	+0.0024	38	7 49 58.7114	3	-0.00235	2	-13 49 16.125	6	+0.0091	3
197 <sup>d</sup>	BD -13°2270	7.8	+1.1			7 50 08.9167	42	+0.00153	30	-13 43 53.664	76	-0.0822	54
198	AC 1088 No. 1940	12.1		+0.0065	34	7 50 18.5982	3	-0.00339	2	-13 49 32.668	5	+0.0151	3
199	BD -13°2274	9.2	+0.7			7 50 30.6043	21	-0.00250	15	-13 45 52.822	30	+0.0096	22
200	vdK-Vys.54	11.9	+0.5	-0.0022	29	7 50 39.9811	2	-0.00378	2	-13 36 07.684	4	+0.0266	3
201	BD -13°2277	8.8	+0.9			7 50 41.0282	44	-0.00326	31	-13 55 38.137	51	-0.0045	36
202	BD -13°2278	9.8	+0.1			7 50 57.8016	13	-0.00261	9	-14 05 16.646	35	-0.0011	25

<sup>a</sup> ADS 6419.  $\theta = 121^{\circ}.27$  and  $\rho = 2^{\circ}.80$  at 1950.196 and  $\theta = 122^{\circ}.12$  and  $\rho = 3^{\circ}.02$  at 1969.855.

<sup>b</sup> Reduced by a sector of 0.33% transmission to 12.0.

<sup>c</sup> Uncatalogued visual double.  $\theta = 308^{\circ}.85$  and  $\rho = 2^{\circ}.99$  at 1950.196 and  $\theta = 308^{\circ}.08$  and  $\rho = 3^{\circ}.25$  at 1969.855.

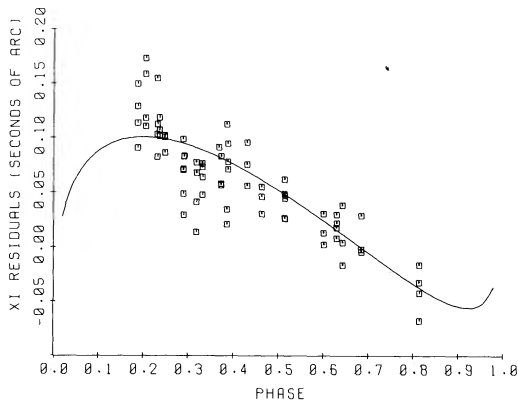
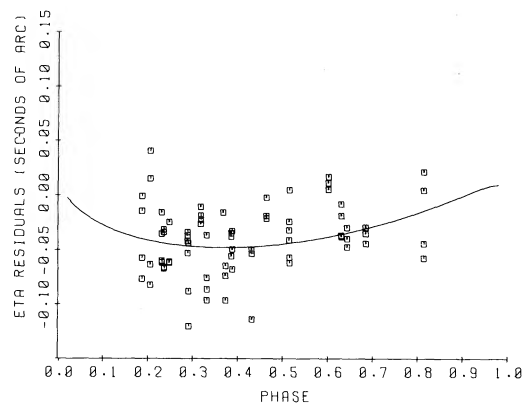
<sup>d</sup> ADS 6426. Type K2 III.  $\pi_{ab} = -0^{\circ}.007 \pm 0^{\circ}.013$  (Jenkins 1952).

with the average reference star magnitude and galactic latitude (van Altena 1974).

Previous parallax determinations have yielded values with an unusually large range. These values and their estimated external standard errors, adjusted according to the precepts of Jenkins (1952), are Cape,  $+0^{\circ}.072 \pm 0^{\circ}.018$  (Jones and Jackson 1935); McCormick,  $+0^{\circ}.031 \pm 0^{\circ}.016$  (Mitchell and Reuyl 1940); Sproul,  $+0^{\circ}.067 \pm 0^{\circ}.012$  (van de Kamp 1939); Van Vleck,  $+0^{\circ}.060 \pm 0^{\circ}.008$  (Grossenbacher and Mesrobian 1969); Yale,  $+0^{\circ}.084 \pm 0^{\circ}.013$  (Alden 1929); and Yerkes,  $+0^{\circ}.059 \pm 0^{\circ}.016$  (Moffitt 1932). The weighted mean so computed is  $+0^{\circ}.0628 \pm 0^{\circ}.0050$ . Combining the above values with the one computed here,  $+0^{\circ}.0608 \pm 0^{\circ}.0044$ , we find a parallax of  $+0^{\circ}.0616 \pm 0^{\circ}.0031$ , which will be

adopted for further use. We note that the unweighted mean of all determinations is  $+0^{\circ}.062 \pm 0^{\circ}.006$ . Some of the scatter in the observed parallaxes may be due to neglect of the corrections for orbital motion.

The residuals of a position, proper motion, and parallax determination for 9 Puppis, i.e., before inclusion of a term for the photocentric semimajor axis, are plotted against phase relative to periastron for  $\xi$  in Fig. 1 and for  $\eta$  in Fig. 2. The residuals have been corrected for the effect of the orbit on the star constants; thus, the zero point of the residuals is the barycenter of the system. The solid curves indicate the motion of the photocenter implied by the Douglass orbit and the value found for the magnitude of the photocentric semimajor axis,  $\alpha_{pg} = +0^{\circ}.117 \pm 0^{\circ}.011$ .

FIG. 1. The  $\xi$  residuals of 9 Puppis.FIG. 2. The  $\eta$  residuals of 9 Puppis.

If both components are main sequence, or if they depart equally therefrom, the photographic magnitude difference is 0.7. A value of  $\Delta m_{pg}$  can also be calculated from a knowledge of  $\alpha_{pg}$  and  $\alpha_v$  (Gatewood and Behall 1975). Adopting  $\alpha_v = +0''.104$  as the weighted mean of the two visual studies mentioned earlier, we calculate  $\Delta m_{pg} = 0.7$ . Thus, we conclude that our assumed  $\Delta m_{pg}$  is trustworthy. If we adopt a standard error of  $\pm 0^m.2$  for  $\Delta m_{pg}$ , we find a theoretical blend effect of  $\beta_{pg} = 0.344 \pm 0.042$ . This  $\Delta m_{pg}$  and the total color index imply individual color indices of  $+0.57$  and  $+0.7$ .

From Douglass' orbit and the adopted parallax, we derive a total mass of  $M_A + M_B = 1.85 \pm 0.32 M_\odot$ . Our values of  $\alpha_{pg}$ ,  $\beta_{pg}$ , and the semimajor axis of the visual orbit yield a fractional mass for the companion of  $B = 0.534 \pm 0.045$ . Hence, we find the individual masses  $M_A = 0.86 \pm 0.17 M_\odot$  and  $M_B = 0.99 \pm 0.19 M_\odot$ .

The individual apparent visual magnitudes of  $5.65 \pm 0.07$  and  $6.25 \pm 0.13$ , the adopted parallax, and the bolometric correction for G-type main-sequence stars (Harris 1963) lead to absolute bolometric magnitudes of 4.54 and 5.1, respectively. These masses and luminosities are well within their errors of the empirically determined mass-luminosity relation.

Thus, we conclude that the 9 Puppis system is composed of two rather normal solar-type stars. However, there is an indication that the brighter star is the less massive. This is the conclusion of two out of three studies, with the third (van de Kamp 1939) concluding equal masses. It would seem that the primary, which is probably not more massive than the secondary, emits 74% more energy in the visual part of the spectrum.

Our plate measurements and standard coordinates are available in punched-card form upon request.

#### ACKNOWLEDGMENTS

The authors wish to express their gratitude to Mr. Geoffrey Douglass for allowing us to use and publish his visual orbit. We are also indebted to Dr. K. Aa. Strand and Dr. Paul M. Routly, also of the U. S. Naval Observatory, for their grant of measuring time on the SAMM engine.

The majority of the plate material was acquired by Dr. N. E. Wagman and Mr. J. Rachuba. The data reductions were carried out on the PDP-1077 computer of the University of Pittsburgh Computer Center.

The first author would also like to acknowledge the support of the Zaccheus Daniel Foundation.

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