Accepted to ApJ Letters

The Algol triple system spatially resolved at optical wavelengths

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ABSTRACT

Interacting binaries typically have separations in the milli-arcsecond regime and hence it has been challenging to resolve them at any wavelength. However, recent advances in optical interferometry have improved our ability to discern the components in these systems and have now enabled the direct determination of physical parameters. We used the Navy Prototype Optical Interferometer to produce for the first time images resolving all three components in the well-known

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **The Algol triple system spatially resolved at optical wavelengths**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Naval Observatory,Flagstaff Station, 10391 W. Naval Obs. Rd,Flagstaff,AZ,86001**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**15**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Algol triple system. Specifically, we have separated the tertiary component from the binary and simultaneously resolved the eclipsing binary pair, which represents the nearest and brightest eclipsing binary in the sky. We present revised orbital elements for the triple system, and we have rectified the 180-degree ambiguity in the position angle of Algol C. Our directly determined magnitude differences and masses for this triple star system are consistent with earlier light curve modeling results.

Subject headings: astrometry — binaries: eclipsing — techniques: interferometric — stars: individual(Algol)

1. Introduction

Algol (β Per, HR 936), the prototype for a well known class of eclipsing binaries, has well over 200 years of published observations available for study. The eclipsing nature of the system was first suggested by Goodricke (1783) when he stated the light variations could result from "... the interposition of a large body revolving around Algol ...". A long suspected third component in Algol was spectroscopically confirmed by Struve & Sahade (1957) and Ebbighausen (1958). Söderhjelm (1980) provides a review of Algol which is a useful starting point for summarizing this triple system. We will refer to the B-type primary star in Algol as Algol A, the K type secondary star as Algol B, and the more distant Am companion as Algol C (see Richards 1993, for the exact spectral types). It is thus a hierarchical triple system as defined by Evans (1968). Wade & Hjellming (1972) made the first radio detection of Algol and Lestrade et al. (1993) determined that the radio emission in Algol comes from Algol B using multi-epoch Very Long Baseline Interferometry observations. Algol was one of 12 radio stars used to link the HIPPARCOS optical reference frame to the International Celestial Reference System (ICRS) (Kovalevsky et al. 1997). The 1.86 year orbit of Algol C was resolved by speckle interferometry (Labeyrie et al. 1974) and optical interferometry (Pan et al. 1993) but these investigations could not resolve the close binary. Also, these results suffer from a 180° ambiguity in the absolute position angle (PA) due to a lack of phase information (Labeyrie 1970). The Fourth Catalog of Interferometric Measurements of Binary Stars has a more complete listing of these observations[1].

This considerable body of knowledge still leaves room for additional exploration, and permitted inconsistent descriptions of the orbital elements of the triple system. It would

[1] http://www.usno.navy.mil/USNO/astrometry/ optical-IR-prod/wds/int4 (Hartkopf et al. 2001a)

appear that the orbital elements listed in Söderhjelm (1980) and Pan et al. (1993) would adequately describe the Algol triple system. But these elements include a 180° difference in the position angle of the ascending node when compared with the orbital solution in the Hipparcos catalog (Lindegren et al. 1997). Algol's role as one of a small number of radio stars used to link the HIPPARCOS optical reference frame to the ICRF requires resolution of this inconsistency. Algol can also serve as a position angle calibrator for optical and near-IR interferometers and this strengthens the case for a resolution of this disagreement.

Recently, Algol was observed in the near IR ($K_s = 2.133\ \mu$m) with the CHARA array and at 5 GHz with the European VLBI Network during December 2006 (Csizmadia et al. 2009). The CHARA array with approximately 200 m baselines has a similar spatial resolution to the NPOI at optical wavelengths with 64 m baselines. The CHARA data resolve the close binary but Csizmadia et al. (2009) make no mention of detecting Algol C. Csizmadia et al. use their VLBI and CHARA array observations to produce an orbit of Algol A−B with an opposite sense of rotation from that determined by Lestrade et al. (1993). We are then presented with another inconsistency in published results for the Algol system.

During 2006 October and November we collected observations of Algol using the Navy Prototype Optical Interferometer (NPOI), the Very Long Baseline Array (VLBA)[2], and the Lowell Observatory 42" Hall telescope equipped with the solar−stellar spectrograph. We defer discussion of the radio and spectroscopic results for a future paper. The primary aim of this project was to resolve the close pair in Algol with the NPOI, and perform an absolute astrometric registration of the optical NPOI images to the ICRF phase-referenced VLBA images. As the NPOI records visibility squared and closure phase data we can determine the position angle calibration without a 180° ambiguity and resolve the inconsistency between the orbital elements in Söderhjelm (1980) and Pan et al. (1993) and the orbital elements in the HIPPARCOS catalog. We can also address the inconsistency in the direction of the close binary orbit between Lestrade et al. (1993) and Csizmadia et al. (2009).

In this paper, we report on our NPOI observations which extend the direct knowledge of the Algol triple system to optical wavelengths. In §2 we discuss our observations, with particular attention to the calibration of the NPOI absolute position angles. In §3 we present the astrometric orbits of the Algol A−B and AB−C systems. We conclude with §4 and a comparison with light curve solutions and a discussion of the astrometric results.

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

2. Observations and Calibration

Algol was observed with the NPOI from 1997 October to 2008 October (see Table 2). The NPOI is a six element optical interferometer, described in detail in Armstrong et al. (1998). Details regarding the general NPOI observational setup and data recording can be found in Hummel et al. (2003) and Benson et al. (2003). We combined the astrometric siderostats on the center (AC), east (AE), and west (AW) stations with the E6 and W7 imaging siderostats. The addition of the latter allowed projected baselines of up to 64 m in length, separated by about 60 degrees in position angle. Up to three baselines were recorded on each of the two spectrometers. We switched between two different four-station configurations half-way through the night. Post-processing of the data was performed using C. Hummel's OYSTER software package. The calibrator star for the 2006 observations was ϵ Persei (HR 1220, V=2.89, B0.5V, parallax (π) = 6.06 mas), located 9.6° from Algol and an estimated diameter (d_{est}) of 0.43 mas based on its $R - I$ color (Mozurkewich et al. 1991; White & Feierman 1987). The 2008 observations included ϵ Per, check binary γ Per (HR 915), and an additional calibrator for γ Per, ϵ Cassiopeiae (HR 542, V=3.34, B3III, $\pi = 7.38$ mas, $d_{est} = 0.43$ mas). The uncertainties on the estimated diameters are 10%. Since γ Per is 16.2° from ϵ Per, Algol and γ Per could share the same calibrator. ϵ Cas then serves as a secondary check on the calibration.

To verify the absolute NPOI PA calibration using our 2008 Oct 27 observation of γ Per we fit a model to the observed squared visibilities and triple phases in OYSTER and imaged γ Per using DIFMAP (Shepherd 1997; Shepherd et al. 1994). The expected position of γ Per was 163.0 mas at 244.6° with an expected R band magnitude difference of 1.5−1.6 (Prieur et al. 2003). We observed γ Per at a position of 160.92 ± 0.28 mas at $244.95 \pm 0.22°$ and a magnitude difference (800nm) of 1.50 ± 0.08. The same result was obtained for both choices (ϵ Per or ϵ Cas) of the calibrator stars which verifies the absolute PA calibration of the NPOI.

3. Analysis and results

The combined visibility data for each night allow the determination of the relative positions of the components. Note that the orbital motion of the A−B pair is significant during each night's observation. Reliable estimates of the magnitude differences were available in the literature and were used as an initial guess in our model fits. The dominant feature of a finite magnitude difference between the C component and the combined light of the A−B pair in the data is the pronounced sinusoidal variation of the squared visibilities. Superimposed on this variation is a subtle modulation due to the (larger) magnitude difference of the close binary itself. The magnitude differences in the V ($\Delta V = 2.92$) and Cousins-I ($\Delta I = 2.63$) bands between the eclipsing pair and component C was determined previously by Pan et al. (1993) using the Mark III Stellar Interferometer. An initial estimate for the magnitude difference between A and B was determined from the light curve analysis by Richards et al. (1988) in the V band ($\Delta V = 3.92$), and we estimated the value for the NPOI 800 nm filter ($\Delta I = 2.6$) using the effective temperatures and log g values of Richards (1993) and the Kurucz model atmospheres (Kurucz 1979). As a check, the same procedure correctly reproduces the J-band magnitude difference given by Richards et al. (1988). Since the diameters are only barely resolved we adopted the values given in Richards et al. (1988) for components A, B, and C, converted to angular diameters using the parallax of Algol of 35.1 mas (distance 28.5 pc, distance modulus 2.27, ESA (1997)). The stellar parameters initially used to model the Algol triple system are listed in Table 1 and were kept fixed for the fits of the relative component positions to refine the orbital elements. After these initial refinements of the orbital elements we also fit for the masses.

Initial astrometric results (separation and position angle) were obtained by using an image for each night to provide an initial guess for the separation and position angle. Algol and γ Per were analyzed in the same manner. Images of Algol were made using AIPS (van Moorsel et al. 1996), DIFMAP and BSMEM (Buscher 1994). Figure 1 illustrates the motion of Algol B over two epochs and the location of Algol C with uniformly weighted images made with DIFMAP. This guess was refined in a fit to the visibility data directly. As typically done in the reduction of NPOI data, we used a fraction of the CLEAN beam (20% in this case) to provide a more realistic estimate of the uncertainty ellipse since the formal errors from the fit to the visibility data usually underestimate the true uncertainty in the results. These initial astrometric results were used to derive an initial fit for the orbital elements.

For the A−B orbit we fixed the eccentricity e to zero (Söderhjelm 1980). We used the photometric light elements (Kim 1989) for the A−B orbit, and the inclination from the light curve analysis (Richards et al. 1988). A fit was then performed for the position angle of the ascending node Ω, and semi-major axis a. The Na D lines of Algol B detected by Tomkin & Lambert (1978) and their orbital elements do verify that we have correctly identified the quadrant of the ascending node of Algol A−B.

For fitting the AB−C orbital elements we began with the orbital elements of Pan et al. (1993) and then corrected the position angle of the ascending node. We solved for all the orbital elements. Again, comparison with spectroscopic data (Ebbighausen 1958; Hill et al. 1971) verify that the quadrant of the ascending node is correctly identified.

In the final step, these orbital elements were refined by comparing them with the visibility data for each scan. Our final astrometric results appear in Table 2. Differential corrections due to the orbital motion of the A−B pair are included in Table 2 based on the orbital elements listed in Table 3. These differential corrections were first applied to NPOI data for close binaries as described in Hummel et al. (1995). The relative positions in Table 2 between composite components in the hierarchical triple, i.e. AB-C, refer to the photocenter of AB.

Using the Algol C orbital elements we again solved for the magnitude differences (B and C relative to A) and the three elements (a, Ω & P) of the A−B pair. A final fit for the stellar masses was performed using the radial velocities contained in Tomkin & Lambert (1978); Hill et al. (1971) and Hill et al. (1993) for Algol A, B, and C. The masses in Table 1 served as initial guesses for the fits. The results and uncertainties are given in Table 3. Figure 2 shows the orbits of the Algol system with the astrometric data.

4. Discussion

Our discussion of the analysis of the interferometric observations will be restricted to the new insights we have gained on this well studied system. Our NPOI observations mark the first resolution of the Algol system into three components. Csizmadia et al. (2009) reported the resolution of the close binary with the CHARA array at near infrared wavelengths but without absolute phase calibration. Our orbital solution is fully consistent with the pioneering radio interferometric observations of Lestrade et al. (1993). We have unambiguously determined that the close pair orbit is retrograde, and nearly orthogonal to the plane of the wide orbit. The relative angle ϕ is $96° \pm 5°$ according to

$$\cos\phi = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos(\Delta\Omega),$$

where i_1 and i_2 are the inclinations of the two orbits, and $\Delta\Omega$ is the difference between the two ascending node angles. This improvement to the orbital plane orientation is relevant to dynamical studies of hierarchical triples (e.g. Kiseleva et al. 1998). This orientation of the wide orbit also removes the discrepancy expected between the photocenter motion one would compute using the AB−C elements of Pan et al. (1993) and that found from HIPPARCOS or the orbit of Heintz (1994). Our retrograde orientation of the close binary orbit contrasts with the prograde orbit of Csizmadia et al. (2009). The position angle calibration of Csizmadia et al. (2009) depended on VLBI observations made during a radio flare of Algol which may have complicated their analysis due to the changing radio morphology of Algol (§4.1 of Csizmadia et al. 2009). As the NPOI observations are calibrated to produce an absolute position angle as shown in §2 (with γ Per as the position angle calibrator) we are confident that the retrograde orbit of the close binary pair is correct. The 15 GHz VLBI observations of Peterson et al. (2010) also agree with the previously determined retrograde orbit.

The absolute position angle calibration of the NPOI enables a revision of the orientation of the Algol C orbit of Pan et al. (1993). Our results place the maximum AB−C separation in the same quadrant as found by Heintz (Heintz 1994; Gatewood et al. 1995). The Hipparcos orbital solution (ESA 1997, Double and Multiple Systems Annex) references Gatewood et al. (1995) for the quadrants of the longitude of periastron ω and the position angle of the ascending node Ω, and our observations confirm the accuracy of the Hipparcos orbital elements. This confirmation is important because it links results from both the optical and radio reference frames. A 180° reversal of the position angle of the ascending node of the AB−C orbit presented here would create a time variable systematic offset of the photocenter (Gatewood et al. 1995) that could not be reconciled with the HIPPARCOS observations.

Our interferometric observations have resulted in the first resolved images of the triple system and the first directly measured magnitude differences for the three stars in Algol. Previous estimates of the magnitude difference for the close binary were made by modeling photometric and spectroscopic data (e.g. Kim 1989; Richards et al. 1988, and references therein). The V band magnitude differences predicted from these models span slightly more than one magnitude: 3.72 ± 0.10 (Wilson et al. 1972), 2.97 ± 0.31 (Söderhjelm 1980), 3.92 ± 0.88 (Richards et al. 1988), and 2.71 ± 0.15 (Kim 1989). Our directly measured V band magnitude differences (Table 3) favor magnitude differences of less than 3. Our AB−C magnitude difference is in excellent agreement with the previously determined value using the Mark III (Pan et al. 1993) and it is also consistent with an early speckle interferometry result (Labeyrie et al. 1974). We extrapolated the magnitude difference to the center wavelength of the Hipparcos Hp filter using the stellar atmosphere parameters from Table 1, and used the masses given in that table to determine a 18.4 mas amplitude for the motion of the photo center. This result is consistent with the Hipparcos orbital solution of 19.0 ± 0.6 mas (ESA 1997). The dynamical parallax determined from our full fit to the astrometric data and published radial velocities is 34.7 ± 0.6, consistent with the Hipparcos value of 35.1 ± 0.9 mas.

Our magnitude differences add a directly measured constraint to the results obtained from modeling the photometric light curve and spectroscopic data. It may be useful to re-examine the modeling of the close binary using magnitude differences derived directly from the interferometer measurements. Other bright double and multiple stellar systems will yield similar constraints for use with spectroscopic and photometric data.

The Navy Prototype Optical Interferometer is a joint project of the Naval Research Laboratory and the US Naval Observatory, in cooperation with Lowell Observatory, and is funded by the Office of Naval Research and the Oceanographer of the Navy. The authors would like to thank Jim Benson and the NPOI observational support staff whose efforts made this project possible. S. Bosken & G. Shelton of the USNO Library were very helpful in our literature search. RTZ is thankful for the support of the Fizeau Exchange Visitor Program through the European Interferometry Initiative (EII) and OPTICON (an EU funded framework program, contract number RII3-CT-2004-001566). This work was partially supported by National Science Foundation grant AST-0908440 to Richards. The literature search made use of the NASA ADS abstract service, the SIMBAD database maintained at CDS, Strasbourg, France and the JSTOR archives. We thank an anonymous referee for numerous suggestions which improved the paper.

Facilities: NPOI ()

Table 1. Adopted and Derived System Parameters

Parameters	Stellar Component A	B	C
Diameter (mas)	0.77	0.93	0.37
Mass ($M_\odot$)[a]	3.7± 0.3	0.81± 0.05	1.6± 0.1
$T_{\rm eff}$(K)[a]	13000	4500	7500
log g	4.0	3.5	4.5

Note. — Values for diameters calculated as described in §3. The log(g) values are from Richards (1993) rounded to match the atmosphere models we used. Diameter, $T_{\rm eff}$ and log g were fixed during the model-fitting. The masses here were initial estimates in the model fitting and the final mass results and uncertainties are listed in Table 3.

[a]Richards (1993)

Table 2. NPOI Relative Astrometric Results

UT Date	JY (yrs)	AB-C ρ (mas)	AB-C θ (deg)	A-B ρ (mas)	A-B θ (deg)	Error Ellipse[a] σ_{maj} (mas)	Error Ellipse[a] σ_{min} (mas)	Error Ellipse[a] ϕ (deg)	Φ
1997 Oct 16	1997.7901	100.63	309.22	...	...	0.996	0.334	2.0	...
1997 Oct 17	1997.7928	100.94	309.96	...	...	0.790	0.366	168.0	...
1999 Mar 4	1999.1700	12.11	228.86	...	...	1.360	0.396	133.9	...
2006 Oct 19	2006.7976	50.56	300.60	2.08	226.49	1.006	0.256	9.6	0.78
2006 Oct 20	2006.8004	51.56	299.26	1.98	48.10	1.056	0.270	5.0	0.14
2006 Oct 23	2006.8086	53.38	299.58	2.54	41.01	1.002	0.248	181.5	0.18
2006 Oct 27	2006.8195	55.30	301.52	1.25	248.71	0.572	0.256	-1.4	0.57
2006 Oct 28	2006.8223	56.32	301.79	1.29	216.29	0.660	0.222	169.6	0.93
2006 Oct 29	2006.8250	57.36	301.01	2.05	54.25	0.460	0.286	153.2	0.27
2006 Oct 30	2006.8277	57.38	302.45	1.95	230.14	0.668	0.232	173.4	0.62
2006 Oct 31	2006.8305	58.26	302.82	...	...	0.440	0.272	146.0	...
2006 Nov 1	2006.8332	58.78	301.49	1.80	43.12	1.014	0.228	123.5	0.32
2006 Nov 2	2006.8360	59.21	302.73	2.06	227.45	0.944	0.232	119.1	0.67
2006 Nov 3	2006.8387	60.16	302.22	...	...	0.924	0.204	129.3	...
2006 Nov 4	2006.8414	60.55	301.92	1.52	40.09	0.886	0.220	125.4	0.36
2006 Nov 5	2006.8442	60.95	303.31	2.33	227.33	1.506	0.238	100.0	0.72
2006 Nov 6	2006.8469	62.08	302.41	1.43	75.06	0.866	0.242	106.1	0.06
2008 Oct 27	2008.8208	83.00	306.52	...	...	0.564	0.292	11.1	...

Note. — Col. 1: UT Date of observation; Col. 2: Julian year at 7 hours UT; Cols. 3-6: separation, position angle (from north through east) for the AB-C and A-B components, respectively; Col. 7: Semi-major axis of error ellipse; Col. 8: Semi-minor axis of error ellipse; Col. 9: Position angle of error ellipse; Col. 10: Close binary orbital phase Φ using light elements $2441773.49 + 2.8673285 * E$ (Kim 1989). Φ of $0.0 \equiv$ primary eclipse, $0.5 \equiv$ secondary eclipse.

[a]The error ellipse is the uncertainty in the location of the position vector. For component C this is with respect to the AB photocenter.

Table 3. Obital Solution And Component Parameters

Orbital Element	A−B Söderhjelm (1980)	A−B This work	AB−C Pan et al. (1993)	AB−C This work
a (mas)	2.2 ± 0.1	2.3 ± 0.1	94.61 ± 0.22	93.8 ± 0.2
i (deg)	81.4 ± 0.2[a]	98.6 [c]	83.98 ± 0.09	83.7 ± 0.1
Ω (deg)	132 ± 4	47.4 ± 5.2	312.26 ± 0.13	132.7 ± 0.1
e	0	0	0.225 ± 0.005	0.225 ± 0.005
ω (deg)	···	···	310.29 ± 0.08	310.8 ± 0.1
T_0 (JY)	···	1973.2471[b]	1987.3689	1987.3689
T_0 (JD)	···	2441773.49[b]	2446931.4 ± 1.5	2446931.6 ± 0.1
P (days)	2.8673	2.867328	680.05 ± 0.06	679.85 ± 0.04
P (years)	···	···	1.8619 ± 0.0002	1.8613 ± 0.0001
π_{dyn} (mas)				34.7 ± 0.6
Magnitude Differences				
Components	Δm(550nm)	Δm(800nm)		
A−B	2.70 ± 0.3	2.20 ± 0.3		
A−C	2.8 ± 0.2	2.6 ± 0.2		
AB−C	2.9 ± 0.1	2.7 ± 0.1		
Masses ($M_\odot$)				
M(A)	3.7 ± 0.2			
M(B)	0.8 ± 0.1			
M(C)	1.5 ± 0.1			

[a]Richards et al. (1988)

[b]Minimum light of primary eclipse

[c]i > 90° used to indicate retrograde motion as defined by Heintz (1978).

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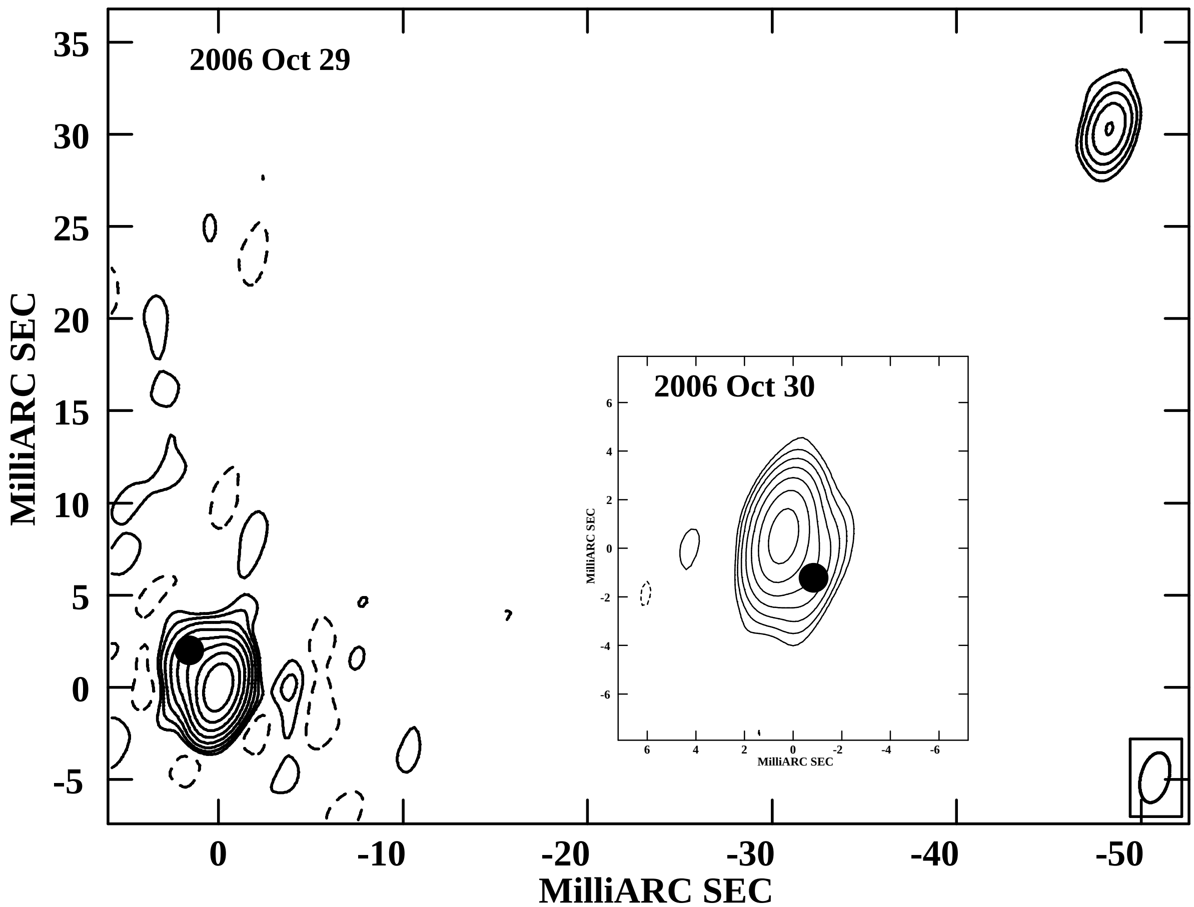

Fig. 1.— An image of the Algol triple system made from the NPOI data of 2006 Oct 29. Algol C is the component in the upper right hand corner. The inset shows a close-up image made from the NPOI observation of 2006 Oct 30 and emphasizes the motion of Algol B between the two epochs. To guide the eye the approximate positions of Algol B are indicated at each epoch by a filled black circle. The uniformly weighted restoring beam is shown in the lower right hand corner.

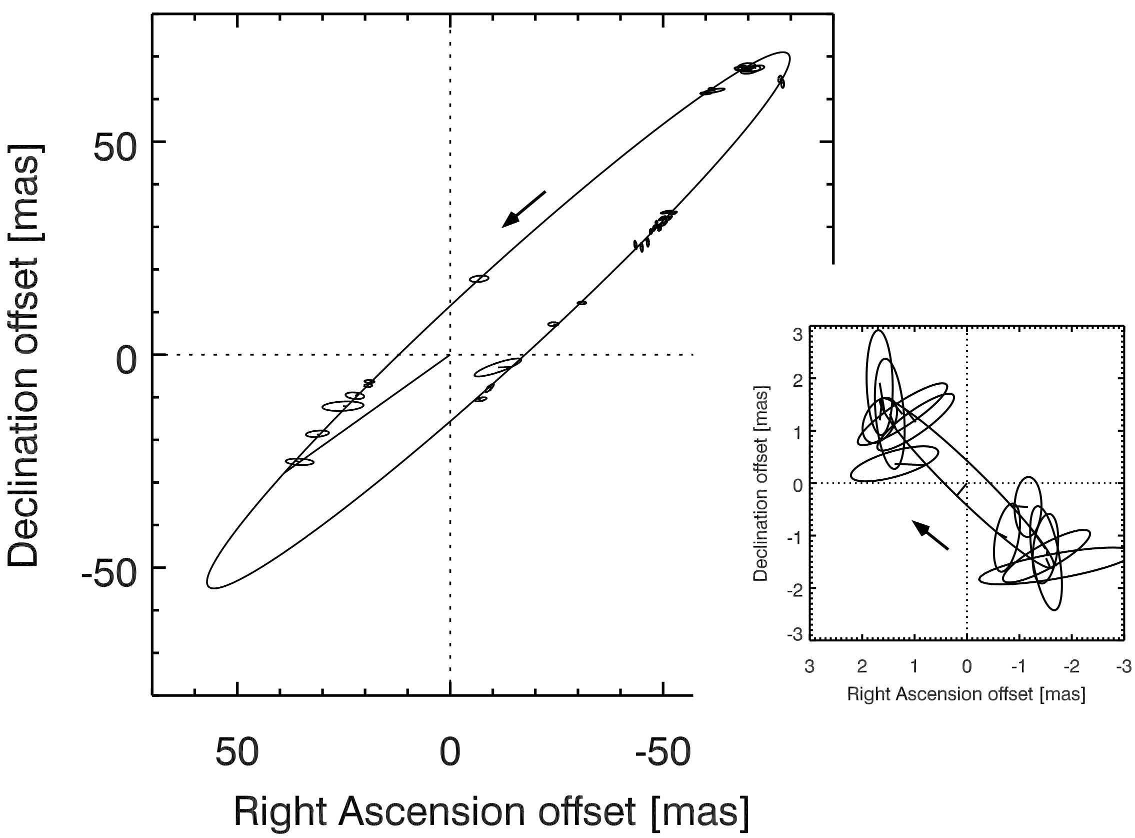

Fig. 2.— The large figure illustrates the AB−C orbit. A vector from the origin indicates the periastron point. The inset figure shows the A−B orbit with a vector from the origin indicating the position of primary eclipse minimum light. The astrometric results of Table 2 are plotted with the astrometry of Pan et al. (1993) rotated by 180° and the orbital elements in Table 3. Uncertainty ellipses are 20% of the CLEAN beam for the NPOI data. Astrometric positions are fit to the individual 30 second scans. The plotted positions for A−B are computed at UT07:00 on the date of observation between 2006 Oct 19 and 2006 Nov 06. Arrows show the direction of the orbital motion on the sky.