Interferometric Observations of Algol

Tamás Borkovits,1 Szilárd Csizmadia,2,3 Zsolt Paragi,4,3, László Sturmann,5 Judit Sturmann,5 Chris Farrington,5 Harold A. McAlister,5 Theo A. ten Brummelaar,5 Nils H. Turner5

Abstract. We determined the spatial orientation of the Algol AB close pair orbital plane using optical interferometry with the CHARA Array, and radio interferometry with the European VLBI Network (EVN). We found the longitude of the line of nodes for the close pair being $\Omega_1 = 48^\circ \pm 2^\circ$ and the mutual inclination of the orbital planes of the close and the wide pairs being $95^\circ \pm 3^\circ$. This latter value differs by $5^\circ$ from the formerly known $100^\circ$ which would imply a very fast inclination variation of the system, not supported by the photometric observations. We also investigated the dynamics of the system with numerical integration of the equations of motions using our result as an initial condition. We found large variations in the inclination of the close pair (its amplitude $\sim 170^\circ$) with a period of about 20 millenia. This result is in good agreement with the photometrically observed change of amplitude in Algol’s primary minimum.

1 Introduction

Algol consists of a semi-detached eclipsing binary with an orbital period of 2.87 days (B8V + K2IV) with an F1IV spectral type star revolving around the binary every 680 days. The third component was successfully observed by speckle interferometry, and its orbit was precisely determined by Bonneau (1979). This result was refined by using the Mark III optical stellar interferometer (Pan, Shao, & Colavita 1993).

In the radio regime, Lestrade et al. (1993) detected positional displacement during the orbital revolution of the AB pair using the VLBI technique, and identified the K-subgiant as the source of radio emission. From their measurements Kiseleva, Eggleton, & Mikkola (1998) calculated $i_m = 100^\circ$ for the mutual inclination of the close and wide orbital planes. This value has been widely accepted since then. However, this mutual inclination value cannot be correct due to dynamical considerations, because it would produce a fast variation in the observable inclination of the eclipsing subsystem, resulting in a fast eclipse

---

1 Baja Astronomical Observatory, H-6500 Baja, Szegedi út, Kt. 766, Hungary
2 Institute of Planetary Research, DLR Rutherfordstr. 2. D-12489, Berlin, Germany
3 MTA Research Group for Physical Geodesy and Geodynamics, H-1585 Budapest, P. O. Box 585., Hungary
4 Joint Institute for VLBI in Europe, Postbus 2, 7990 AA Dwingeloo, The Netherlands
5 Center for High Angular Resolution Astronomy, Georgia State University, P. O. Box 3969, Atlanta, GA 30302
depth variation which contradicts to the more than century-long photometric observations (Söderhjelm 1980).

The aim of this study was to constrain the mutual inclination of the system better, requiring the measurement of the longitude of the node for the close pair. The other orbital elements are well-known from spectroscopic or photometric data, but there is a controversy in the value of $\Omega_1$. Because the expected apparent size of the close binary semi-major axis is of the order of 2 milliarcseconds (mas), we carried out both optical and radio interferometry measurements.

## 2 Observations and results

We carried out interferometric observations both in the optical/near-infrared, and in the radio regime. The optical interferometry observations were done by the CHARA Array on three nights (2, 3 and 4 December, 2006) in the $K_s$ band. The radio measurements were carried out with a subset of the European VLBI Network (EVN) on 14-15 December 2006 at 5 GHz. At this observation the e-VLBI technique was applied, where the telescopes stream the data to the central data processor (JIVE, Dwingeloo, the Netherlands) instead of recording. The participating telescopes were Cambridge and Jodrell Bank (UK), Medicina (Italy), Onsala (Sweden), Toruń (Poland) and the Westerbork phased array (the Netherlands). The measurements and the data reductions were carried out according to the standard procedures. (Details can be read in Csizmadia et al. 2009.)

For the analysis of the CHARA visibilities we developed a model which was very close to the one of Wilson & Devinney (1971) which is based on the Roche-model, but it was implemented in IDL to restore the surface intensities into a matrix and to calculate the sky-projected picture of the system. Since we had only about two dozen visibility measurements, we wanted to limit the number of free parameters, choosing just three: the angular size of the semi-major axis $a_1$, the surface brightness ratio in $K_s$ band $J_{K_s}$, and the angle $\Omega_1$. All other parameters were fixed according to the values given in Wilson et al. (1972) or in Kim (1989). After an extended grid search we got $a_1 = 2.28 \pm 0.02\,\text{mas}$, $J_{K_s} = 0.330 \pm 0.01$, and $\Omega_1 = 48^\circ \pm 2^\circ$, respectively.

The VLBI data were gained during a secondary minimum, which, according to our simultaneous optical photometry, occurred at $t_0 = 2454084.360 \pm 0.003$ (Bíró et al. 2007). The measurements lasted 9 hours, i.e. $\approx 13\%$ of the orbital period, but as the projected movement of the source is maximal around the minima, the covered projected orbital arc is significantly larger. Due to the large inclination, this projected arc is almost a straight line parallel to the nodal line, which makes the determination of the longitude of the node more easier. Unfortunately, during our measurements a radio flare occured which significantly reduced the accuracy of our position determination. Our best fit gave $\Omega_1 = 52^\circ \pm 3^\circ$, but we consider this result less reliable because it is difficult to assess how much the radio flare as well as atmospheric phase fluctuations might have affected our data (e.g. the displacement of the source during our observation was almost twice of the calculated from Keplerian revolution).

Due to the above mentioned facts, here we concentrate mainly on the CHARA results. The true size of the obtained semi-major axis and surface
brightness ratio are in very good agreement with previous results, which makes our nodal result also plausible. According to the CHARA results, the longitude of the node is $\Omega_1 = 48^\circ \pm 2^\circ$ with an ambiguity of $180^\circ$. With the VLBI measurements we can resolve the $\pm 180^\circ$ ambiguity and conclude that $\Omega_1 = 48^\circ \pm 2^\circ$. This is in excellent agreement with the value determined from polarimetric measurements ($\Omega_1 = 47^\circ \pm 7^\circ$, Rudy 1979), indicating that polarimetry is an efficient tool to determine the spatial orientation of the orbits.

At this point we can determine the mutual inclination $i_m$, and we get $i_m = 95^\circ \pm 3^\circ$. This value is, however, closer to the exact perpendicularity than the $100^\circ$ which was based on the measurements of Lestrade et al. (1993).

3 Dynamics of the system

In order to investigate the dynamical behaviour of Algol in the near past and future, we carried out numerical integration of the orbits for the triple system. Detailed description of our code can be found in Borkovits, Forgács-Dajka, & Regály (2004). This code simultaneously integrates the equations of the orbital motions and the Eulerian equations of stellar rotation. The code also includes stellar dissipation, but the short time interval of the data allows that term to be ignored. Our input parameters for Algol AB were taken from Kim (1989) with the exception of $\Omega_1$ which was set to $48^\circ$ in accordance with our CHARA result. The
orbital elements of the wide orbit were almost identical to the elements given by Pan et al. (1993). As further input parameters, the $k_2$, $k_3$ internal structure constants for the binary members were taken from the tables of Claret & Giménez (1992).

Here we consider only the observable inclination of the eclipsing pair. The computed variation of inclination between 7500 BC and 22 500 AD was plotted in Fig. 1. Note that Algol AB does not show eclipses when the inclination is lower than 63° or higher than 117°. It shows partial eclipses if the inclination is between 63°–117° and moreover, it shows total eclipses when the inclination 87.3°–92.7. As one can see, Algol started to show eclipses shortly after the beginning of the Christian calendar. Total eclipses occurred during an almost 300-year-long interval at the end of the medieval, and at the dawn of the modern, scientific era. According to our integrations in the time of the discovery as a variable star (Montanari 1671), the inclination of the close pair was about 88° which yielded a total eclipse (with an amplitude of 2.8 mag, when the bright primary component is totally eclipsed, and the dominant light source is the distant C component), making discovery easier. However, it should be emphasized that this time-data are rough approximations only. Since we could not determine the position of the node better than ±2°, and for exact calculations one needs an accuracy better by one order of magnitude, these numbers should be refined in the future.

Considering the scientific era, one can see that our result suggests an inclination variation of $\Delta i \approx -1°.6$ in the last century which is in accordance with the statement of Söderhjelm (1980).

Acknowledgments. The CHARA Array is funded by the National Science Foundation through NSF grants AST-0307562 and AST-06006958 and by Georgia State University through the College of Arts and Sciences and the Office of the Vice President for Research.

e-VLBI developments in Europe are supported by the EC DG-INFSO funded Communication Network Developments project ‘EXPReS’, Contract No. 02662. The European VLBI Network is a joint facility of European, Chinese, South African and other radio astronomy institutes funded by their national research councils.

Zs.P. acknowledges support from the Hungarian Scientific Research Fund (OTKA, grant no. K72515).

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France and has made use of NASA’s Astrophysics Data System.

References

Biró, I.B., Borkovits, T., Hegedűs, T. et al. 2007, IBVS 5753
Bonneau, D. 1979, A&A, 80, 11
Borkovits T., Forgács-Dajka, E., Regály Zs. 2004, A&A, 426, 951
Claret, A., & Giménez, A. 1992, A&AS, 96, 255
Csizmadia, Sz., Borkovits, T., Paragi, Zs. et al. 2009, ApJ, submitted
Kim, H. I. 1989, ApJ, 342, 1061
Kiseleva, L. G., Eggleton, P. P., Mikkola, S. 1998, MNRAS, 300, 292
Lestrade, J. F., Phillips, R. B., Hodges, M. W., Preston, R. A. 1993, ApJ, 410, 808
Montanari, G. 1671, Sopra la sparizione d’alcune stelle ed altre novità celesti
Pan, X., Shao, M., Colavita, M. M. 1993, ApJ, 413, 129
Rudy, R. J. 1979 MNRAS, 186, 473
Söderhjelm, S. 1980, A&A, 89, 100
Wilson, R. E., Devinney, E. J. 1971, ApJ, 166, 605
Wilson, R. E., de Luccia, M., Johnston, K., Mango, S. A. 1972, ApJ, 177, 191