NEW INSIGHTS INTO THE NATURE OF THE ECLIPSING SYSTEM V609 AQUILAE

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A photometric study of the near-contact binary (NCB) system V609 Aql reveals it to be the westernmost star of a close double, with brightness variations and implied parameters more extreme than those derived in an earlier photographic study, in which images of the variable and companion were almost certainly blended. The system's brightness variations exhibit deep primary eclipses ($\Delta V = 1\cdot04$) and secondary eclipses ($\Delta V = 0\cdot44$) matched to a model fit with a derived orbital inclination of $i = 84^{\circ}\cdot8 \pm 0^{\circ}\cdot2$ and estimated component spectral types of F8–F9 and K2–K3. The primary overfills its Roche lobe in the optimum eclipse solution, inconsistent with the definition of NCBs. Period changes in the system are studied from 23 published times of light minimum and 21 newly-established values: 18 from examination of archival Harvard plates, and three from ASAS data and new CCD observations. O – C variations from 1891 to 2007 exhibit a long-term parabolic trend indicative of a period decrease, $dP/dt = -(7\cdot75 \pm 1\cdot39) \times 10^{-8}$ d yr^{-1}, corresponding to mass transfer to the secondary of $(6\cdot5 \pm 1\cdot2) \times 10^{-8}\ M_{\odot}$ yr^{-1}. Superposed variations may indicate fluctuations in the mass flow. The system is estimated to be $\sim$513 pc distant.

Introduction

The number of well-studied eclipsing binary systems in the Galaxy is a small fraction of the number listed in the 1969 and 1985 editions of the *General Catalogue of Variable Stars*[1,2], and some systems with several bibliographic entries in the ADS (Astronomical Data System) may be relatively poorly studied. A good example is V609 Aquilae (2000 co-ordinates $20^h\ 09^m\ 58^s\cdot77$, $+14^{\circ}\ 38'\ 14''\cdot7$), originally described as an Algol-like variable[3], but now recognized as a β Lyrae system[4], primarily from a photographic study by Ishtchenko & Leibowitch[5]. The same study appears to be the basis for later summaries of more detailed system parameters and the object's designation as a detached system[6], as well as the cited spectral types of the component stars as F8 and G0[7]. With a period $P = 0^d\cdot796565 = 19\cdot1$ hours, V609 Aql undergoes a primary or secondary eclipse most clear evenings, making it ideal for observational study.

In 1994 V609 Aql was included in a list of near-contact binaries (NCB)[8], a new subclass of close-binary systems (CBS) defined by Shaw[9]. NCB systems have periods of less than a day, exhibit the effects of tidal interaction, and have facing surfaces less than 0·1 orbital radius apart, but are not in contact. Such systems may be the evolutionary precursors to the A-type W UMa systems, and are probably in the early stages of mass transfer. NCBs may also be X-ray sources, although V609 Aql itself is not detected in the *ROSAT* All-Sky Survey[10].

In *An Atlas of O – C Diagrams of Eclipsing Binary Stars*[11] V609 Aql is noted to be a β Lyrae-type or W UMa-type system, but insufficiently researched. Only 19 times of light minimum over the interval 1937 to 1996 are cited, including unpublished results. Four additional times of light minimum since 2000 have been published[12,13,14,15], increasing the number of such estimates to 23. But the only publicly available light curve for the star[5] was derived from visual inspection of plates in the collection of Tashkent Astronomical Observatory, and is not of high precision.

Our interest in V609 Aql originated with its remarkable O – C diagram, which displays irregular trends[11]. We therefore initiated a new study of the system in order to find additional times of light minimum, the intent being to clarify the nature of its period variability. V609 Aql was therefore observed photometrically to establish times for current minima, and was also investigated using the Harvard College Observatory Photographic Plate Collection to obtain archival or 'historical' times of minima. As we describe here, our new observations for V609 Aql reveal it to be a much more interesting and different system than found by previous investigators.

Observational data and O – C analysis

New *V*-band observations were obtained for V609 Aql on 21 nights between 2006 September 22 and December 18 using a Celestron 28-cm Schmidt-Cassegrain telescope at the Abbey Ridge Observatory (Lane), an automated facility located at a dark site outside of Halifax, Nova Scotia. The telescope is equipped with a SBIG ST9 CCD camera and an Optec IFW filter wheel, although for the present study of V609 Aql only *V* observations were measured. All data represent means for combinations of short-exposure images that were analyzed by aperture photometry and normalized relative to GSC 01085–01422, our adopted reference star for the field (at an adopted magnitude of $V = 10 \cdot 59$), with HDE 354987 and three other stars in the field serving as check stars (see Table I and Fig. 1). The standard deviations for all observations of the reference star and check stars were ± $0^m \cdot 006$ to ± $0^m \cdot 008$, typical of other observations being made from the observatory. The data are summarized in Table II.

Additional observations of V609 Aql were obtained on one night (2006 October 7) using the 70-cm telescope of the Kalinenkov Astronomical Observatory of Nikolaev State University, equipped with a SBIG ST-7 camera in an instrumental photometric system closely approximating the standard *V*-band. The CCD exposures for the observations were of shorter duration than those obtained from Abbey Ridge, in an attempt to prevent image overlap for the newly-discovered companion star (see below). The resulting data represent means of ten separate exposures, obtained by aperture photometry and tied to the same reference stars. Unfortunately, residual image overlap contaminates the photometry, making it difficult to calibrate relative to our reference stars, although the data display excellent overall agreement with our primary observations when combined with them after normalization (Table III).

TABLE I

Reference stars for observations of V609 Aql

Star	*RA(2000)*	*Dec(2000)*	*V*	*Notes*
V609 Aql	$20^h\ 09^m\ 58^s \cdot 58$	$+14^\circ\ 38'\ 12'' \cdot 9$	var	
Companion	$20^h\ 09^m\ 58^s \cdot 94$	$+14^\circ\ 38'\ 12'' \cdot 9$	12·35	See text, $5'' \cdot 6$ separation
Std	$20^h\ 10^m\ 17^s \cdot 43$	$+14^\circ\ 35'\ 07'' \cdot 1$	10·59	GSC 01085–01422
C1	$20^h\ 10^m\ 21^s \cdot 40$	$+14^\circ\ 36'\ 28'' \cdot 8$	9·77	HDE 354987
C2	$20^h\ 10^m\ 16^s \cdot 74$	$+14^\circ\ 41'\ 01'' \cdot 3$	11·07	
C3	$20^h\ 09^m\ 52^s \cdot 00$	$+14^\circ\ 38'\ 07'' \cdot 9$	12·35	
C4	$20^h\ 10^m\ 03^s \cdot 65$	$+14^\circ\ 40'\ 26'' \cdot 7$	12·68	

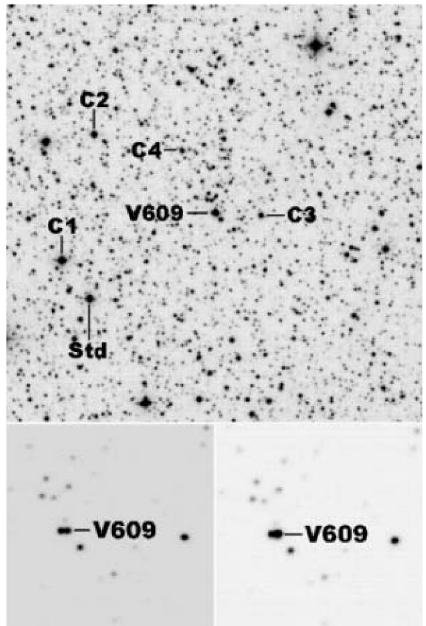

FIG. 1

A finder chart for the field centered on V609 Aql from the red image of the Palomar Observatory Sky Survey (top). The field of view measures $15' \times 15'$ and shows the location of the variable, the adopted reference star, and four check stars used for the observations. The lower portion of the figure displays two enlargements from CCD images of V609 Aql at phases 0·9998 (lower left) and 0·8700 (lower right).

All data for V609 Aql were phased using an existing ephemeris[11], namely:

$$HJD_{min} = 2429365 \cdot 7284 + 0 \cdot 7965639\, E,$$

where E is the number of elapsed cycles.

The phased Abbey Ridge V-band observations of V609 Aql are plotted in Fig. 2. They were initially constrained to only a few hours on each clear night, but the star was also monitored continuously on three nights near the end of the run in an attempt to delineate critical portions of the light curve. Although full phase coverage for the binary system was not obtained, the data are sufficiently complete

TABLE II

New observations for V609 Aql and companion

HJD	*Phase*	*V*	*HJD*	*Phase*	*V*
2454000·5525	0·3628	11·095	2454050·5003	0·0668	11·292
2454000·5510	0·3608	11·095	2454050·4975	0·0633	11·292
2454000·6086	0·4332	11·229	2454050·5027	0·0699	11·265
2454000·6985	0·5461	11·230	2454050·5074	0·0758	11·242
2454001·6424	0·7309	11·026	2454050·5125	0·0821	11·221
2454001·6819	0·7806	11·047[a]	2454050·5174	0·0882	11·195
2454005·5400	0·6240	11·082	2454050·5222	0·0943	11·179
2454005·5951	0·6932	11·036	2454050·5272	0·1006	11·172
2454006·5393	0·8785	11·115	2454050·5319	0·1064	11·156
2454006·6468	0·0134	11·555	2454050·5371	0·1130	11·137
2454009·5083	0·6058	11·107	2454050·5417	0·1188	11·125
2454009·5469	0·6542	11·057	2454050·5468	0·1251	11·111
2454009·6679	0·8061	11·066	2454050·5517	0·1313	11·111
2454014·5487	0·9334	11·320	2454050·5567	0·1377	11·099
2454014·5896	0·9848	11·605	2454050·5620	0·1443	11·093
2454015·5801	0·2283	11·034	2454050·5667	0·1502	11·090
2454015·6180	0·2758	11·018	2454050·5711	0·1556	11·076
2454016·5038	0·3879	11·120	2454051·4683	0·2821	11·028
2454016·5404	0·4338	11·218	2454051·5133	0·3385	11·057
2454017·6510	0·8280	11·069	2454061·4318	0·7902	11·035
2454019·5127	0·1652	11·053	2454061·4318	0·7902	11·035
2454024·4986	0·4245	11·178	2454061·4364	0·7958	11·040
2454024·5393	0·4756	11·304	2454061·4412	0·8019	11·044
2454025·4686	0·6422	11·066	2454061·4462	0·8082	11·054[a]
2454025·5140	0·6991	11·027	2454061·4509	0·8141	11·058[a]
2454025·6108	0·8207	11·066	2454061·4561	0·8206	11·047[a]
2454038·5357	0·0465	11·384	2454061·4607	0·8264	11·060[a]
2454038·5954	0·1214	11·133	2454061·4661	0·8331	11·058[a]
2454041·4385	0·6907	11·028	2454061·4722	0·8409	11·080
2454041·4484	0·7031	11·031	2454061·4771	0·8470	11·083
2454041·4554	0·7119	11·029	2454061·4822	0·8534	11·095
2454041·4624	0·7207	11·020	2454061·4870	0·8594	11·111
2454041·4694	0·7295	11·027	2454061·4923	0·8661	11·111
2454041·4764	0·7383	11·014	2454061·4970	0·8720	11·120
2454041·4834	0·7470	11·022	2454061·5020	0·8783	11·148
2454041·4904	0·7558	11·020	2454061·5069	0·8844	11·151
2454041·4970	0·7641	11·032	2454061·5118	0·8906	11·165
2454041·5053	0·7745	11·021	2454061·5169	0·8970	11·190
2454041·5108	0·7815	11·028	2454061·5217	0·9029	11·207
2454050·4434	0·9954	11·641	2454061·5269	0·9095	11·230
2454050·4434	0·9954	11·641	2454061·5316	0·9154	11·245
2454050·4479	0·0010	11·623	2454061·5366	0·9217	11·296
2454050·4528	0·0071	11·609	2454061·5400	0·9259	11·298
2454050·4579	0·0136	11·570	2454062·5201	0·1563	11·082
2454050·4627	0·0196	11·536	2454081·4531	0·9247	11·284
2454050·4680	0·0262	11·498	2454082·4309	0·1522	11·084
2454050·4828	0·0448	11·398	2454082·4723	0·2042	11·037
2454050·4876	0·0509	11·357	2454088·4494	0·7077	11·018
2454050·4928	0·0573	11·324			

[a] Observation of low quality.

that one can map almost a complete light curve by using the symmetry of the light curves of close binaries and mirroring the data about primary minimum (lower portion of Fig. 2). Mirroring the light curve also allowed us to estimate the time of primary minimum accurately using the robust software used for matching Cepheid light curves[17], the result being a derived phase shift of $\Delta\varphi = -0{\cdot}0097 \pm 0{\cdot}0018$, corresponding to $O-C = +0^{d}{\cdot}0077 \pm 0{\cdot}0018$, the uncertainty

TABLE III

Nikolaev observations of V609 Aql

HJD	*Phase*	*V*
2454029·2410	0·3781	11·538
2454029·2486	0·3876	11·565
2454029·2597	0·4015	11·613
2454029·2657	0·4091	11·626
2454029·2734	0·4187	11·693
2454029·2793	0·4262	11·674
2454029·2871	0·4360	11·712
2454029·2932	0·4436	11·766
2454029·3064	0·4602	11·795
2454029·3239	0·4821	11·842
2454029·3349	0·4959	11·830
2454029·3527	0·5182	11·756
2454029·3597	0·5270	11·708
2454029·3743	0·5454	11·675
2454029·3804	0·5530	11·657
2454029·3851	0·5589	11·626

established by the fitting procedure used to minimize the resulting scatter in the data matched through mirroring. The corresponding time for primary minimum associated with the start of cycle 30989, following which we began a continuous run on V609 Aql, is HJD 2454050·4548 ± 0·0014. That value is listed in Table IV.

In similar fashion the single-night observations for V609 Aql observed from Nikolaev were used to delineate a secondary minimum for the system, and yielded an O – C datum through mirroring. That result is listed in the second-last row of Table IV.

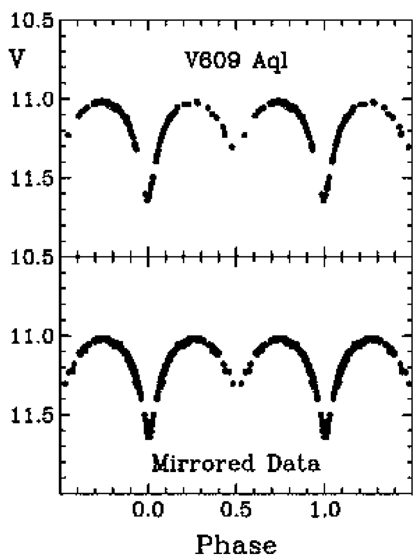

FIG. 2

V-band CCD observations for V609 Aql from the present programme (upper). Open circles depict low-quality observations. The lower portion of the figure displays the same data mirrored about zero phase.

TABLE IV

Newly derived epochs of minimum light for V609 Aql

$HJD_{min}(obs)$	Cycle (E)	$HJD_{min}(calc)$	O – C (d)	Year
2411964·6344	–21845·0	2411964·7900	–0·1556	1891
2412348·5912	–21363·0	2412348·7338	–0·1426	1892
2412360·5611	–21348·0	2412360·6823	–0·1212	1892
2412368·5377	–21338·0	2412368·6479	–0·1102	1892
2414925·5472	–18128·0	2414925·6180	–0·0708	1899
2414933·5536	–18118·0	2414933·5837	–0·0301	1899
2414947·4798	–18100·5	2414947·5235	–0·0437	1899
2415289·5874	–17671·0	2415289·6477	–0·0603	1900
2415548·9022	–17345·5	2415548·9293	–0·0271	1901
2415618·5976	–17258·0	2415618·6286	–0·0310	1901
2415724·5048	–17125·0	2415724·5716	–0·0668	1901
2416639·7569	–15976·0	2416639·8235	–0·0666	1904
2416785·5235	–15793·0	2416785·5947	–0·0712	1904
2417094·5966	–15405·0	2417094·6615	–0·0649	1905
2418543·5561	–13586·0	2418543·6113	–0·0552	1909
2421092·5566	–10386·0	2421092·6157	–0·0591	1916
2428426·5910	–1179·0	2428426·5796	+0·0114	1936
2433484·7483	+5171·0	2433484·7603	–0·0120	1950
2453872·7789	+30766·0	2453872·8133	–0·0344	2006
2454029·3323	+30962·5	2454029·3382	–0·0059	2006
2454050·4548	+30989·0	2454050·4471	+0·0077	2006

We also obtained an estimate for the time of light minimum using *V*-data from the ASAS-3 (All Sky Automated Survey 3) project[17] matched to our resulting light curve adjusted for the phase offset. The ASAS-3 data exhibit a phase shift of $\Delta\varphi = -0{\cdot}0432$ relative to our best-fitting light curve, and also match the present observations to within a few millimagnitudes in *V*. The resulting O – C value ($-0^{d}{\cdot}0344$) is listed in the third-last row of Table IV.

Additional estimates for times of light minimum in V609 Aql, both primary and secondary minima, were obtained through visual scanning of plates in the Harvard College Observatory (HCO) Photographic Plate Collection, using suitable reference stars in the field for comparison[5]. A selection of patrol-series plates was initially scanned for that purpose, but with limited success. Most patrol-series exposures are roughly an hour in duration, which corresponds to a range in phase of ~0·05. By chance most early patrol-series exposures of the field of V609 Aql correspond to times outside eclipse, and only ~1% of those examined (two) reveal the star near light minimum. Many higher-resolution plates were exposed near times of mid-eclipse, however, and proved to be a more reliable source of data. Most of the high-resolution plates have exposure times of order 10 minutes, corresponding to an uncertainty in phase of less than ± 0·01.

In that manner we were able to estimate 18 times of light minimum for V609 Aql from 1891 to 1950, two being times of secondary minimum. The data are tabulated for reference purposes in Table IV.

The resulting O – C data are plotted in Fig. 3 (upper panel) as filled and open circles. From an analysis of all times of light minima we find the following parabolic solution:

$$HJD_{min} = (2429365{\cdot}7233 \pm 0{\cdot}0062) + (0{\cdot}796566 \pm 0{\cdot}000003)\,E - (0{\cdot}845 \pm 0{\cdot}151) \times 10^{-10}\,E^2$$

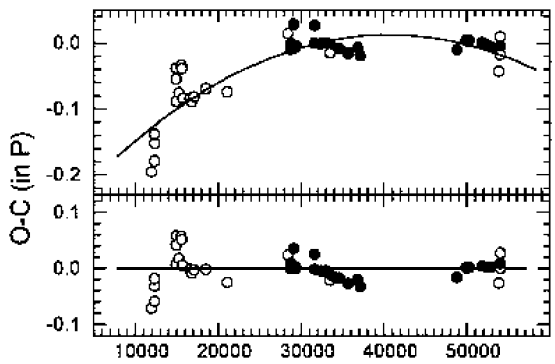

FIG. 3

O – C data (in units of phase offset) for V609 Aql plotted as a function of observed (HJD – 2 400 000) of light minimum (upper). The lower plot shows the same data after removal of the parabolic trend evident in the data in the upper portion of the figure. Filled circles denote published times of light minimum, open circles the data of this paper.

The parabolic fit is shown in Fig. 3 (upper panel). The period is clearly decreasing, the measured rate being $dP/dt = -(7{\cdot}75 \pm 1{\cdot}39) \times 10^{-8}$ d yr^{-1}. There may be additional trends in the O – C variations, but the evidence is not well established.

The scatter resulting from meshing the mirrored observations with the actual observations is only about $\pm\, 0^{m}{\cdot}011$ for the optimum fit, not much larger than the estimated uncertainties in the data. Given the range of nights and phase over which the observations were obtained, such small residuals suggest that any non-symmetric deviations of the actual light curve arising from starspots or an accretion disc are negligibly small. In fact, both features were considered in modelling the system, but were found to be unimportant.

Light-curve analysis

It seems clear from our new light curve for V609 Aql (Fig. 2) that the system undergoes deeper eclipses than implied by the original photographic study[5]. Another unexpected discovery from the CCD observations is that the star is an optical double. The lower portion of Fig. 1 contains two CCD images, one near light minimum (lower left) and one near light maximum (lower right), illustrating that the eclipsing system is the westernmost (right hand) star of the pair. The two stars are only 5·6 arcseconds apart (Table I) and the pair is always blended in our observations, so the data of Table II refer to the combined light of both stars, as established from aperture photometry.

Reliable separation of the light of the variable from the combined light of the pair requires knowledge of the brightness of the contaminating star, which is not readily established. Our Nikolaev observations generated magnitude estimates for both stars separately, but contain residual contamination arising from scattered light from the neighbouring star, which was eliminated by normalizing the data to the Abbey Ridge data. We were also unable to derive reliable estimates for the two stars through crude profile fitting methods, owing to the pixel scale for the CCD. Instead, we were able to solve for the brightness of the (assumed) non-variable optical companion of V609 Aql by proceeding as follows.

TABLE V

Reduced observations for V609 Aql

Phase	*V*	*Phase*	*V*	*Phase*	*V*	*Phase*	*V*
0·0002	12·439	0·1811	11·452	0·5056	11·842	0·8254	11·436
0·0059	12·402	0·1869	11·446	0·5082	11·830	0·8255	11·463
0·0104	12·365	0·1891	11·463	0·5196	11·826	0·8300	11·445
0·0120	12·373	0·1932	11·432	0·5275	11·795	0·8313	11·455
0·0183	12·267	0·1993	11·426	0·5306	11·756	0·8329	11·468
0·0184	12·296	0·2050	11·419	0·5394	11·708	0·8380	11·452
0·0245	12·230	0·2050	11·419	0·5441	11·766	0·8389	11·486
0·0311	12·159	0·2091	11·422	0·5509	11·709	0·8395	11·478
0·0496	11·982	0·2137	11·409	0·5517	11·712	0·8430	11·489
0·0514	11·958	0·2146	11·436	0·5578	11·675	0·8450	11·498
0·0557	11·913	0·2207	11·399	0·5613	11·690	0·8457	11·484
0·0617	11·852	0·2310	11·415	0·5615	11·674	0·8509	11·502
0·0622	11·858	0·2331	11·418	0·5620	11·707	0·8518	11·488
0·0681	11·806	0·2393	11·398	0·5654	11·657	0·8575	11·511
0·0692	11·816	0·2481	11·400	0·5690	11·693	0·8583	11·505
0·0705	11·794	0·2569	11·389	0·5707	11·629	0·8639	11·529
0·0735	11·813	0·2642	11·406	0·5712	11·626	0·8643	11·529
0·0747	11·763	0·2657	11·408	0·5786	11·626	0·8700	11·529
0·0798	11·732	0·2745	11·398	0·5861	11·613	0·8709	11·529
0·0806	11·727	0·2806	11·395	0·6001	11·565	0·8737	11·561
0·0856	11·709	0·2833	11·410	0·6072	11·542	0·8763	11·549
0·0870	11·695	0·2869	11·409	0·6096	11·538	0·8768	11·542
0·0922	11·673	0·2874	11·395	0·6106	11·523	0·8822	11·567
0·0931	11·655	0·2921	11·413	0·6289	11·486	0·8831	11·584
0·0982	11·647	0·2960	11·408	0·6343	11·505	0·8833	11·535
0·0991	11·630	0·3020	11·420	0·6471	11·463	0·8887	11·596
0·1046	11·609	0·3045	11·409	0·6566	11·450	0·8892	11·588
0·1054	11·620	0·3410	11·450	0·6590	11·450	0·8946	11·620
0·1108	11·588	0·3434	11·450	0·6955	11·409	0·8954	11·609
0·1113	11·596	0·3529	11·463	0·6980	11·420	0·9009	11·630
0·1167	11·535	0·3657	11·505	0·7040	11·408	0·9018	11·647
0·1169	11·584	0·3711	11·486	0·7079	11·413	0·9069	11·655
0·1178	11·567	0·3894	11·523	0·7126	11·395	0·9078	11·673
0·1232	11·542	0·3904	11·538	0·7131	11·409	0·9130	11·695
0·1237	11·549	0·3928	11·542	0·7167	11·410	0·9144	11·709
0·1263	11·561	0·3999	11·565	0·7194	11·395	0·9194	11·727
0·1291	11·529	0·4139	11·613	0·7255	11·398	0·9202	11·732
0·1300	11·529	0·4214	11·626	0·7343	11·408	0·9253	11·763
0·1357	11·529	0·4288	11·626	0·7358	11·406	0·9265	11·813
0·1361	11·529	0·4293	11·629	0·7431	11·389	0·9295	11·794
0·1417	11·505	0·4310	11·693	0·7519	11·400	0·9308	11·816
0·1425	11·511	0·4346	11·657	0·7607	11·398	0·9319	11·806
0·1482	11·488	0·4380	11·707	0·7669	11·418	0·9378	11·858
0·1491	11·502	0·4385	11·674	0·7690	11·415	0·9383	11·852
0·1543	11·484	0·4387	11·690	0·7793	11·399	0·9443	11·913
0·1550	11·498	0·4422	11·675	0·7854	11·436	0·9486	11·958
0·1570	11·489	0·4483	11·712	0·7863	11·409	0·9504	11·982
0·1605	11·478	0·4491	11·709	0·7909	11·422	0·9689	12·159
0·1611	11·486	0·4559	11·766	0·7950	11·419	0·9755	12·230
0·1620	11·452	0·4606	11·708	0·7950	11·419	0·9816	12·296
0·1671	11·468	0·4694	11·756	0·8007	11·426	0·9817	12·267
0·1687	11·455	0·4725	11·795	0·8068	11·432	0·9880	12·373
0·1700	11·445	0·4804	11·826	0·8109	11·463	0·9896	12·365
0·1745	11·463	0·4918	11·830	0·8131	11·446	0·9941	12·402
0·1746	11·436	0·4944	11·842	0·8189	11·452	0·9998	12·439

Inspection of our image of the system near primary minimum indicates that the eclipsing system is marginally fainter than the companion at that epoch. The limits for eye detection of brightness differences between stars is typically[18] $\sim 0^m\cdot 1$, so we estimated the brightness of the optical companion by subtracting its light from the combined-light data using various trial values, until the brightness of V609 Aql at primary minimum was $\sim 0^m\cdot 1$ fainter. The result was a companion at $V = 12\cdot 35$, identical in brightness to check star C3, which lies conveniently close to the pair. The images of star C3 in the lower portion of Fig. 1 are sufficiently close in apparent size and brightness to those for the eastern optical companion of V609 Aql to confirm its inferred magnitude, although it is clearly a result in need of verification.

We summarize in Table V the inferred uncontaminated brightness of V609 Aql from the Abbey Ridge and Nikolaev observations, including mirrored values, and plot the data in Fig. 4. The results are clearly at variance with previous conclusions concerning the depths of primary and secondary minimum, and also about the brightness of the star in and out of eclipse (see Table VI).

We modelled the light curve for V609 Aql using BINARY MAKER 3[19] along with reasonable estimates for the properties of the two components. A low-dispersion (120 Å mm^{-1}) spectrogram of the system near light maximum, taken with the DAO's *Plaskett* telescope, implies a spectral type of ~F8–9 V, consistent with previous estimates[7], but the spectral type of the fainter star in the system cannot be established directly, except through analysis of the light curve. We found through trial and error, in conjunction with examination of the residuals for various trials, the solution given in Table VI. An initial temperature for the primary was established from its F8–F9 V spectral type, corresponding to an intrinsic $B-V$ colour of 0·54–0·57, in conjunction with the $B-V$ colour–$T_{\rm eff}$ relation of Gray[20], which implies $T_{\rm eff}$ = 5988–6083 K. The final solution implies $T_{1\rm eff}$ = 6050 K and $T_{2\rm eff}$ = 5000 K, the latter corresponding to a K2–K3 dwarf. Both stars are larger than expected for dwarfs, presumably a consequence of stellar evolution and the changes occurring in a close-binary system with mass transfer.

TABLE VI

Derived system parameters for V609 Aql

Parameter	*Ref. 5*	*Ref. 6*	*This Paper*
V	...	...	11·40
ΔV_1	...	...	1·04
ΔV_2	...	...	0·44
B	11·7	...	...
ΔB_1	0·4	...	...
ΔB_2	0·2	...	...
Separation	...	4·97 $R_\odot$	4·39 $R_\odot$
R_1	...	1·49 $R_\odot$	1·84 $R_\odot$
R_2	...	1·24 $R_\odot$	1·47 $R_\odot$
RL_1	...	74%	113%
RL_2	...	71%	98%
L_1	...	2·34 $L_\odot$	2·70 $L_\odot$
L_2	...	1·43 $L_\odot$	0·80 $L_\odot$
T_1	...	5870 K	6050 ± 25 K
T_2	...	5680 K	5000 ± 25 K
M_1	...	1·49 $M_\odot$	1·05 $M_\odot$ (adopted)
M_2	...	1·10 $M_\odot$	0·74 ± 0·02 $M_\odot$
M_1/M_2	...	0·74	0·70 ± 0·02
Sp. T.$_1$	...	F8	F8–F9
Sp. T.$_2$	...	...	K2–K3
i	...	...	84°·8 ± 0°·2

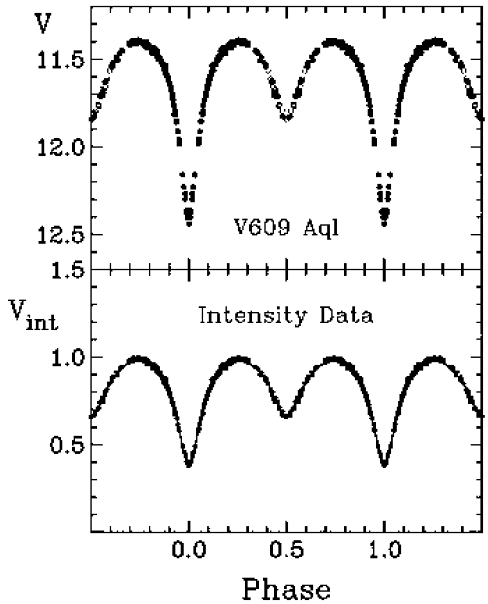

FIG. 4

V-band observations (including mirrored data) for V609 Aql (upper) corrected for contamination by a companion of $V = 12 \cdot 35$. Open circles represent the Nikolaev observations normalized to the Abbey Ridge data. The same data are plotted as intensities (lower) along with the best-fitting model light curve.

The mass ratio for eclipsing systems is difficult to establish without radial-velocity information[21], although our solution yielded reasonable results. A mass of $M_1 = 1 \cdot 05\ M_\odot$ was adopted for the primary from its main-sequence spectral type F8–F9 and luminosity[22], and the eclipse solution yielded a reasonably well-defined mass ratio of $M_2/M_1 = 0 \cdot 70 \pm 0 \cdot 02$. The resulting implied secondary mass of $M_2 = 0 \cdot 72 \pm 0 \cdot 02\ M_\odot$ is, in fact, the value expected for a K2–K3 dwarf[22], apparently confirming the eclipse solution. Although we cannot exclude the possibility of systematic effects in our iterative technique, since the various system properties depend directly upon each other, the results should encourage others to observe the star in a more comprehensive fashion to establish the system parameters more reliably. High-precision radial-velocity observations of the system are essential for confirming the inferred masses of the two components, as well as for constraining the light-curve solution for the system, which is illustrated in the lower portion of Fig. 4.

A model for the V609 Aql system from the eclipse solution is given in Fig. 5. The primary star in the system is indicated to overfill its Roche lobe, since an alternative solution for a star just filling its Roche surface produced clear discrepancies with the observed light curve. The primary is therefore in the process of transferring mass to the secondary. The derived rate of period decrease can be used to find the rate of mass flow from the primary in the system in the case of conservative mass transfer[23], namely from:

$$\frac{dM_1}{dt} = \frac{1}{3P}\frac{dP}{dt}\left(\frac{M_1 M_2}{M_1 - M_2}\right).$$

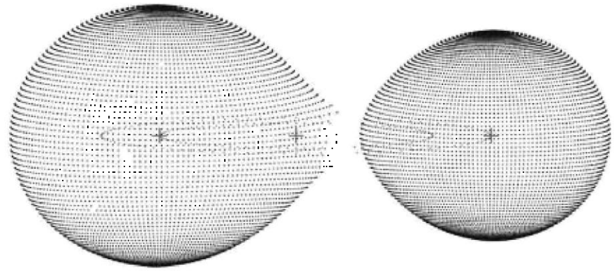

FIG. 5

A model for the V609 Aql system at phase 0·25 from BINARY MAKER 3

In the present case the derived parameters for the system correspond to a rate of mass transfer to the secondary of $(6 \cdot 5 \pm 1 \cdot 2) \times 10^{-8} M_{\odot}$ year^{-1}, atypically large for a close binary system but not for a system in which one star overfills its Roche lobe. The fact that matter from the primary in the system is flowing directly to the secondary without the presence of an accretion disc presumably accounts for the lack of X-rays from the system.

The light curve of V609 Aql bears some similarity to the light curves of the NCBs WZ Cyg[24] and MT Her[25], which have eclipse depths and inferred parameters like those of V609 Aql. However, neither of those systems displays the extreme light-curve curvature of V609 Aql, and both are undergoing period increases rather than a period decrease. They are likely in a different phase of evolution as close-binary systems than V609 Aql. In fact, given all of the available evidence, V609 Aql no longer satisfies the criteria of a NCB, since the primary overfills its Roche surface and both components are oversized. In contrast, most NCBs and their subclasses consist of a primary at or near its Roche lobe, with only the secondary in the system being oversized[8].

The distance to V609 Aql

The eclipse solution for V609 Aql allows one to establish a reasonably reliable estimate for the distance to the system. Although the components are non-spheroidal and in near-contact, the view of the system during secondary eclipse is toward the side of the primary facing away from the secondary. One can adjust the orbital inclination in BINARY MAKER 3 so that secondary eclipse is an occultation, the effective radius of the primary at that instant being $1 \cdot 846\, R_{\odot}$ for the component masses estimated previously. With the effective temperature estimated from the model (which we assume applies to the back hemisphere) and inferred parameters for the Sun[26], we obtain a luminosity for the back hemisphere of the primary of $4 \cdot 095\, L_{\odot}$, or $M_V = +3 \cdot 29$. The light originating from the primary during secondary eclipse is $V = 11 \cdot 84$, resulting in an observed distance modulus of $V - M_V = 8 \cdot 55$.

It can be argued that V609 Aql must be unreddened. The available broadband B and V magnitudes, primarily photographic, refer to the combined light of the optical double, whereas the JHK colours[27] for the individual stars imply that the eastern component is a red star, with $J-H$ colour comparable to unreddened late-type stars of $B-V \cong +1 \cdot 1$. The $J-H$ colour for V609 Aql is that of a yellow dwarf, but uncertainties of as much as $\pm 0 \cdot 1$ in the JHK colours make it difficult to be more specific.

A more direct estimate is made as follows. The assumed spectral type of F8–F9 for the primary corresponds to $(B-V)_0 \cong +0{\cdot}55$. Our photographic estimates of the brightness of V609 Aql on the Harvard plates, and the original study of Ishtchenko & Leibowitch[5], imply $B \cong 11{\cdot}7$ for the combined light of the optical double at light maximum. The eastern component should have $B \cong 13{\cdot}45$ according to our estimates for its visual brightness and broad-band colour, making the brightness of the eclipsing component roughly $B \cong 11{\cdot}94$ at maximum brightness. The observed visual maximum brightness is $V = 11{\cdot}39$, resulting in an observed colour of $B-V \cong +0{\cdot}55$, identical to the expected unreddened broad-band colour. Small changes to the calculations, within the magnitude of potential uncertainties in the estimates, do not alter the results significantly, so it seems clear that any interstellar reddening of the system must be negligibly small.

The field of V609 Aql at Galactic co-ordinates $l = 55^\circ{\cdot}20$, $b = -10^\circ{\cdot}03$ is adjacent to nearby Galactic fields where the reddening has been studied previously[28]. In those fields, stars appear to be unreddened at distances of up to ~ 500 pc, beyond which dust extinction produces colour excesses of $E_{B-V} = 0{\cdot}3$ or larger. Since V609 Aql is unreddened, its implied distance modulus is $V_0 - M_V = 8{\cdot}55$, corresponding to $d = 513$ pc ($\pi = 0''{\cdot}0019$), *i.e.,* roughly the maximum distance beyond which dust extinction becomes important. The solution is consistent with the known spatial distribution of dust in adjacent Galactic fields[28], but is larger than the original estimate of the system's distance[6], which was 385 pc. The difference appears to originate in the larger radii found here for the primary and secondary stars in the system.

Conclusions

From 18 new times of light minimum for V609 Aql obtained from examination of images in the HCO Photographic Plate Collection and three new estimates for light minimum obtained from recent observations of the system, we have calculated a new ephemeris for V609 Aql that includes a parabolic term. The inferred rate of period decrease, $dP/dt = -(7{\cdot}75 \pm 1{\cdot}39) \times 10^{-8}$ d yr^{-1}, implies a rate of mass transfer of $(6{\cdot}5 \pm 1{\cdot}2) \times 10^{-8}\ M_\odot$ year^{-1} from the primary in the system to the less-massive component, the primary overfilling its Roche lobe according to the new eclipse solution presented here. Small irregularities in the rate of period decrease for the system may simply be indicative of inhomogeneities in the rate of mass flow between the two components. The inferred parameters are at variance with the characteristics displayed by other members of the class of near-contact binaries[8], of which V609 Aql can no longer be considered a member.

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THE DOUBLE-LINED BINARY γ CANIS MINORIS

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Since the first detection of the secondary component of γ Canis Minoris by Scarfe[1], enough observations have been obtained for a definitive spectroscopic orbit. The period is close to a year, so adequate phase coverage takes some time. The orbit solution is presented, and the physical nature and evolutionary status of the system discussed. The system is of interest because both components have left the main sequence, and are similar in mass but not in luminosity.