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ASTRONOMY AND ASTROPHYSICS

# S 10947 Aquilae ≡ RX J2009.8+1557: a probable RS CVn star which sometimes stops its eclipses*

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**Abstract.** We report the discovery of a new variable star, called S 10947 Aql, as the likely optical counterpart of RX J2009.8+1557. The optical variability pattern as well as the detected X-ray emission suggest that it is a chromospherically active binary of the RS Canum Venaticorum (≡ RS CVn) type. We discovered an occasional disappearance of the eclipsing minima as well as large variations in the eclipse amplitude. We discuss possible causes of this peculiarity.

**Key words:** stars: binaries: close – stars: circumstellar matter – stars: individual: S 10947 Aql – X-rays: stars

## 1. Introduction

RS Canum Venaticorum (RS CVn) variables are described by Hall (1972; see also Biermann & Hall 1976), as close binaries comprising a G- or K-type subgiant and a F- or G-type star of luminosity class IV–V with the following special property (see also Zeilik et al. 1979): Their light curves are characterized by long waves with amplitudes up to 0.2 mag which, if the binary is eclipsing, as a rule move towards smaller phase of the orbital light curve. This is typically interpreted as the effect of large star spots on one hemisphere of the cool component when rotating with a speed slightly different from the synchronous rotation (e.g. Catalano 1983). Thus, these waves are assumed to be the beat between the orbital period and the slightly out-of-phase differential rotation of the spotted star. The assumption of substantial chromospheric activity is supported by additional observational features, such as strong Ca II emission lines, lively flaring activity in the optical and other spectral regions and variable X-ray emission (e.g. Walter et al. 1980, Schwartz et al. 1981, Charles 1983).

## 2. Observations and discussion

As part of our programme of investigating the optical long-term behaviour of selected ROSAT sources (e.g. Richter et al. 1995) we discovered a new variable star as the likely optical counterpart of RX J2009.8+1557. This object which we called S 10947 Aql, varies in the B band between $13\overset{\rm m}{.}4$ and $14\overset{\rm m}{.}8$. It is identical to GSC 0161801655. The optical coordinates are:

$$\mathrm{R.A.} = 20^{\rm h}09^{\rm m}51\overset{\rm s}{.}43, \mathrm{Dec.} = +15^\circ57'34\overset{\prime\prime}{.}2$$

(equinox 2000.0), consistent with our measurement on the digitized Palomar Sky Survey plate (see marked object in Fig. 1).

RX J2009.8+1557 was detected during the ROSAT all-sky survey in 1990 at a count rate of 0.019±0.005 cts $\mathrm{s}^{-1}$ with a likelihood of detection of 12.4 (corresponding to about $4\sigma$ con-

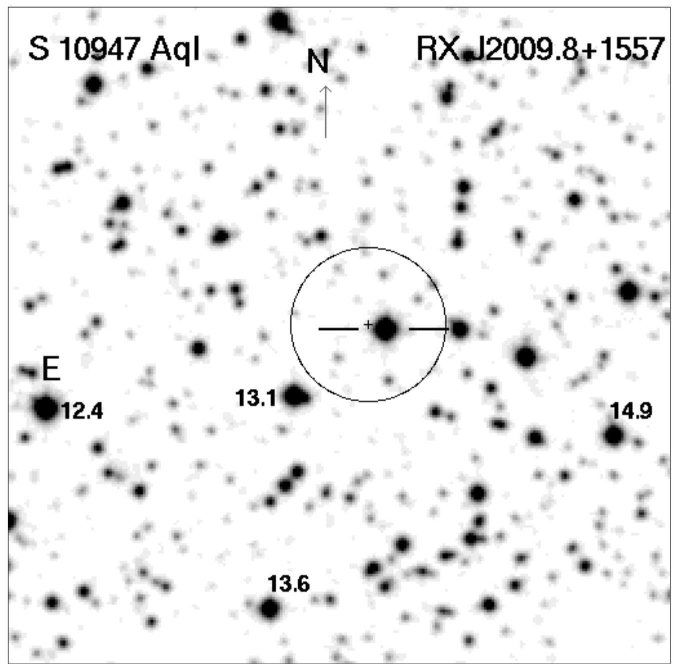


**Fig. 1.** A $4\overset{\prime}{.}3$ by $4\overset{\prime}{.}3$ part of the digitized sky-survey image (based on the red passband plate SF04843 taken on 25 Sep 1992) with the X-ray error circle of the ROSAT all-sky survey position (large circle; $30''$ radius) overplotted. S 10947 Aql is marked by two heavy dashes. The numbers next to 4 other bright stars are photographic magnitudes of the comparison stars (see Table 3) used for deriving the light curve of S 10947 Aql (see Fig. 2). They have been derived by differential connection to comparison stars of WZ Sge (Khruzina & Shugarov 1991).

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* The complete Table 1 is available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

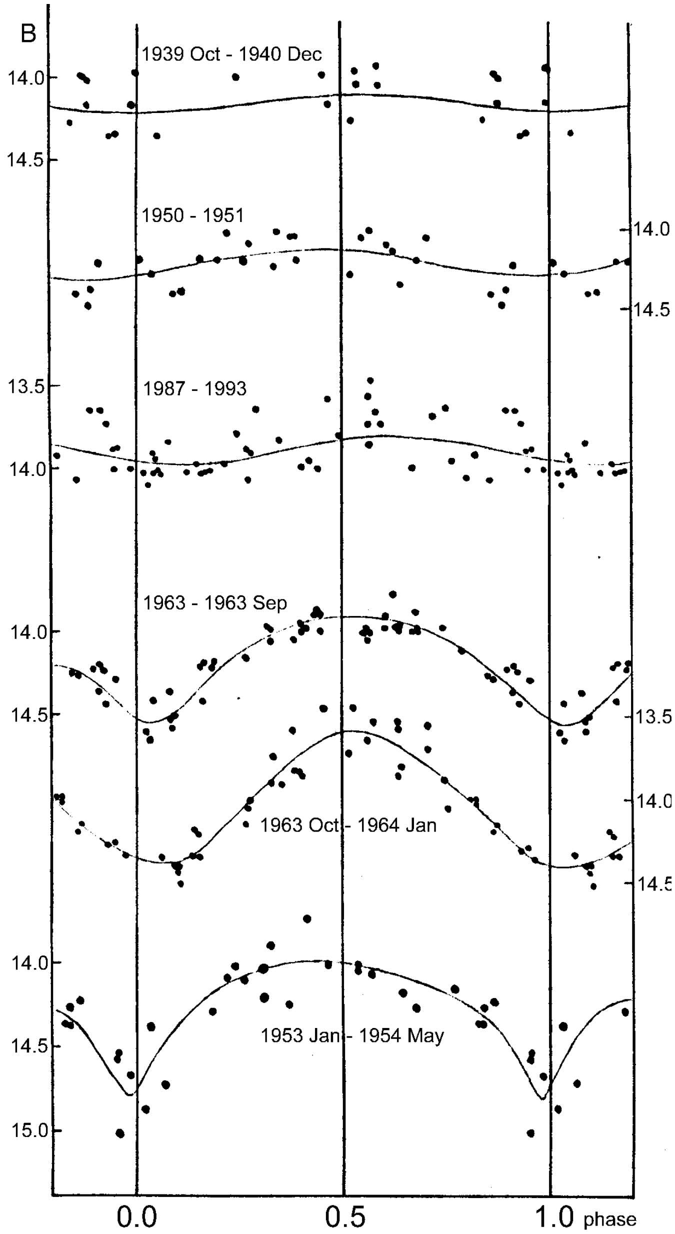


**Fig. 2.** Some examples of light curves without eclipses (upper half) and with eclipses (lower half). Data taken over several month (time span is indicated above each light curve) are folded over $P_{\rm h}$.

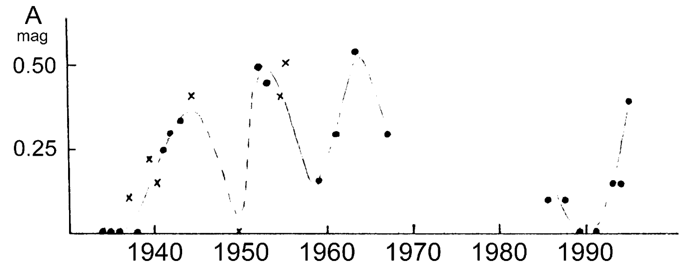


**Fig. 3.** Time variation of the eclipsing amplitude. The time axis is in years, and crosses denote uncertain measurements.

fidence). With a total of only 9 counts collected during the total exposure time of 495 sec this source is below the brightness limit of the 1 RXS catalog (Voges et al. 1999). Nonetheless, these few photons supply both a well-defined position of RA (2000.0) = $20^{\rm h}09^{\rm m}51\overset{\rm s}{.}9$, Decl. (2000.0) = $+15°57'35''$ with an error radius of $30''$ as well as an indication for an absorbed, hard X-ray spectrum (in ROSAT standards). The hardness ratios are HR1 = $(N_{52-201} - N_{11-41})/(N_{11-41} + N_{52-201})$ = 0.70±0.32, and HR2 = $(N_{91-200} - N_{50-90})/N_{50-200}$ = 0.52±0.34, where $N_{\rm a-b}$ denotes the number of counts in ROSAT's position sensitive proportional counter between channel a and channel b). Adopting a Raymond-Smith spectrum with a 1 keV temperature and an absorbing column of $N_{\rm H}=1\times10^{21}$ cm$^{-2}$ (corresponding to ∼50% of the total column of $N_{\rm H}$=1.95×10$^{21}$ cm$^{-2}$ in this direction; Dickey & Lockman 1990) we derive an unabsorbed X-ray intensity of $L(0.1-2.4\ {\rm keV}) = 1.8\times10^{-13}$ erg cm$^{-2}$ s$^{-1}$. This corresponds to an emission measure of 1.3×10$^{52}$ (D/100 pc)$^2$ cm$^{-5}$. No ROSAT pointing exists for this sky area which could allow to derive better constraints.

Altogether 709 archival plates taken between 1934 and 1995 of the Sonneberg astrographs 400 mm, 170 mm and 140 mm were used for investigating the long-term behaviour of S 10947 Aql. Table 1 gives the details of these measurements. Unfortunately, the object is invisible on all plates of the Sonneberg sky patrol.

Spectroscopic observations of S 10947 Aql do not exist, but the kind of brightness changes together with the detected X-ray emission seem to indicate that it is a chromospherically active binary of the RS CVn type.

The major results of the variability study can be summarized as follows:

– We find occasional brightness humps which can be recognized and followed over several months to years, with a cycle length of about $P_{\rm h} = 8\overset{\rm d}{.}628$ (in the mean) and an amplitude of $\lesssim$ 0.5 mag (migrating waves).
– Eclipsing minima occur with a mean period of $P_{\rm o} = 8\overset{\rm d}{.}6294$.
– We observe the occasional disappearance of the eclipsing minima (see Figs. 2 and 3). This is probably only partly caused by the overlapping of the minima with the maxima of the migrating waves. Also, in some other RS CVn stars the depth of the primary minima varies, but it does not approach zero as is the case in S 10947 (e.g. RT Lac: the amplitude varies between about 0.7 and 1.0 mag, see Evren 1989; UX UMa: the amplitude varies from 0.4 to about 0.6 mag, see Geyer 1980).
– During the whole time of observation the period $P_{\rm o}$ is decreasing (Table 2 and Fig. 4). The observed minima may formally be described by

$$m = 242\,9811.30 + 8\overset{\rm d}{.}6321 \times E - 1.14 \times 10^{-6} \times E^2$$

The period of most, if not all, RS CVn stars is changing, but in our case the numerical value of the quadratic term is quite large (see below). Of course, it is not known whether the periods are in reality changing smoothly, or whether the changes are abrupt (polygonal).

**Table 1.** Photometric observations of S 10947 Aql at Sonneberg Observatory. Only the first (seven) and (five) latest measurements are given to indicate the temporal coverage. The number after each plate type gives the total number of plates investigated. The full table is available electronically at CDS.

| HJD (2400000+) | $m_{pg}$ (mag) | Uncert. flag[(1)] |
|---|---|---|
| **A plates (175)** | | |
| 27543.564 | 13.55 | |
| 27546.563 | 13.83 | |
| 27569.510 | 13.63 | |
| 27579.540 | 14.05 | |
| 27612.513 | 13.67 | |
| 27628.505 | 13.59 | |
| 27635.443 | 13.95 | |
| ... | ... | |
| 39765.310 | 13.69 | |
| 40030.462 | 14.35 | |
| 40059.411 | 13.60 | : |
| 40415.454 | 13.59 | |
| 40477.337 | 13.82 | |
| **D plates (140)** | | |
| 33772.546 | 14.16 | |
| 33778.542 | 14.03 | |
| 33809.521 | 14.10 | : |
| 33828.450 | 14.12 | |
| 33834.495 | 14.36 | |
| 33838.426 | 14.00 | : |
| 33855.432 | 14.22 | |
| ... | ... | |
| 35571.609 | 13.71 | |
| 35609.550 | 13.82 | |
| 36343.450 | 14.30 | : |
| 36347.523 | 14.30 | :: |
| 36404.542 | 14.80 | :: |
| **F plates (96)** | | |
| 26928.422 | 14.10 | :: |
| 26931.487 | 14.30 | : |
| 26980.338 | 13.90 | : |
| 27003.276 | 13.93 | |
| 27277.441 | 14.00 | : |
| 27281.425 | 14.30 | : |
| 27298.394 | 13.90 | :: |
| ... | ... | |
| 37246.220 | 13.60 | : |
| 37559.390 | 14.00 | |
| 37824.515 | 13.38 | |
| 37934.428 | 14.00 | : |
| 39352.395 | 13.89 | |
| **GA, GB, GC plates (298)** | | |
| 29054.501 | 14.01 | |
| 29102.537 | 14.35 | |
| 29130.461 | 14.06 | |
| 29162.322 | 14.17 | |
| 29168.367 | 13.92 | |
| 29429.518 | 14.18 | |
| 29438.498 | 14.11 | |
| ... | ... | |
| 49862.479 | 13.59 | |
| 49866.533 | 13.90 | |

**Table 1.** (continued)

| HJD (2400000+) | $m_{pg}$ (mag) | Uncert. flag[(1)] |
|---|---|---|
| **A plates (175)** | | |
| 50246.521 | 13.84 | |
| 50248.516 | 13.68 | |
| 50281.543 | 13.79 | |

[(1)] The symbols have the following meanings: ":" ≡ uncertain, "::" ≡ very uncertain, ">" ≡ upper limit.

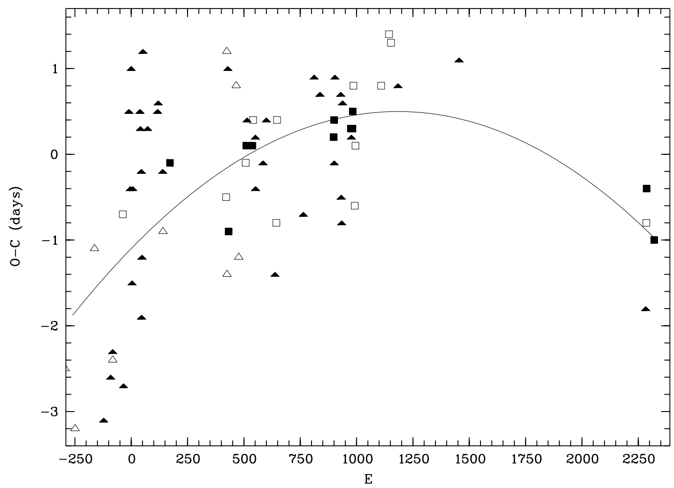


**Fig. 4.** $O-C$ diagram, calculated according to the formula 242 9812.40 + $8.^{d}6294\times E$. The solid line is the best-fit quadratic adaption to the observations: $m$ = 242 9811.30 + $8.^{d}6321 \times E$ - $1.14\times10^{-6} \times E^2$. The symbols have the following meaning: filled triangles = secure isolated observations (error $\pm0.^{d}7$), open triangles = uncertain isolated observations (error $\pm1.^{d}5$), filled squares = secure mean of series observations (error $\pm0.^{d}2$), open squares = uncertain mean of series observations (error $\pm0.^{d}6$).

According to the classical interpretation of RS CVn stars the brightness changes can be interpreted solely by starspot activities in a binary system (e.g. Geyer 1976). But until now it was not yet possible to unambiguously explain the physical processes in RS CVn systems. This is because photoelectric and spectroscopic observations are not available to a sufficient extent since the phenomenon was discovered by Hall (1972).

Systematic changes of the orbital period are observed also in most other RS CVn systems. Hall & Kreiner (1980) and Hall et al. (1980) gave a compilation of 34 such objects where both, decreasing and increasing periods are found in the ratio of about 2:1. The value of $d\log P/dt$ = –2.3 × $10^{-6}$ for S 10947 is large but not extraordinary. It is surpassed only by SZ Psc (–5.25 × $10^{-6}$), CQ Aur (–2.45 × $10^{-6}$) and AR Mon (–1.22 × $10^{-6}$).

In any case, large period changes are an indication of rapid evolutionary efects (e.g. p. 427 in Kopal 1978). However, it is difficult to estimate more details, such as mass loss or mass transfer rates in RS CVn stars because the period changes may be caused by effects which are not directly related to the mass transfer in the binary system. As far as known, RS CVn stars have binary components of similar mass. Though RS CVn stars are

**Table 2.** Observed minima and $O-C$ values

| I(solated) S(eries) | HJD 24... | $m_{\rm pg}$ (mag) | E | $O-C$ | Uncert. flag |
|---|---|---|---|---|---|
| I | 27281.4 | 14.35 | -293 | -2.5 | : |
| I | 27660.5 | 14.26 | -249 | -3.2 | : |
| I | 28404.4 | 14.30 | -163 | -1.1 | : |
| I | 28756.5 | 14.70 | -122 | -3.1 | |
| I | 29024.6 | 14.41 | -91 | -2.6 | |
| I | 29102.4 | 14.28 | -82 | -2.4 | : |
| I | 29102.5 | 14.35 | -82 | -2.3 | |
| S | 29492.4 | 14.32 | -37 | -0.7 | : |
| I | 29516.4 | 14.31 | -34 | -2.7 | |
| I | 29726.6 | 14.34 | -10 | +0.5 | |
| I | 29777.5 | 14.47 | -4 | -0.4 | |
| I | 29813.4 | 14.40 | 0 | +1.0 | |
| I | 29846.4 | 14.37 | 4 | -1.5 | |
| I | 29872.4 | 14.34 | 7 | -0.4 | |
| I | 30149.5 | 14.41 | 39 | +0.5 | |
| I | 30166.5 | 14.50 | 41 | +0.3 | |
| I | 30200.5 | 14.41 | 45 | -0.2 | |
| I | 30207.4 | 14.50 | 46 | -1.9 | |
| I | 30225.4 | 14.47 | 48 | -1.2 | |
| I | 30262.3 | 14.71 | 52 | +1.2 | |
| I | 30442.6 | 14.38 | 73 | +0.3 | |
| I | 30520.5 | 14.34 | 117 | +0.5 | |
| I | 30848.5 | 14.50 | 120 | +0.6 | |
| I | 31020.3 | 14.44 | 140 | -0.2 | |
| I | 31028.3 | 14.31 | 141 | -0.9 | : |
| S | 31296.6 | 14.65 | 172 | -0.1 | |
| S | 33444.9 | 14.53 | 421 | -0.5 | : |
| I | 33472.5 | 14.50 | 424 | +1.2 | : |
| I | 33478.5 | 14.40 | 425 | -1.4 | : |
| I | 33515.4 | 14.37 | 429 | +1.0 | |
| S | 33539.0 | 14.45 | 432 | -0.9 | |
| I | 33834.5 | 14.36 | 466 | +0.8 | : |
| I | 33927.4 | 14.36 | 477 | -1.2 | : |
| S | 34196.0 | 14.50 | 508 | -0.1 | : |
| S | 34222.1 | 14.50 | 511 | +0.1 | |
| I | 34248.4 | 14.80 | 514 | +0.4 | |
| I | 34334.3 | 14.60 | 524 | +0.1 | |
| S | 34455.1 | 14.70 | 538 | +0.1 | |
| S | 34481.3 | 14.60 | 541 | +0.4 | : |
| I | 34567.4 | 14.90 | 551 | +0.2 | |
| I | 34575.5 | 15.20 | 552 | -0.4 | |
| I | 34860.6 | 14.60 | 585 | -0.1 | |
| I | 34990.4 | 14.78 | 600 | +0.4 | |
| I | 35316.5 | 14.60 | 638 | -1.4 | |
| S | 35368.9 | 14.60 | 644 | -0.8 | : |
| S | 35396.0 | 14.60 | 647 | +0.4 | : |
| I | 36404.5 | 14.80 | 764 | -0.7 | |
| I | 36820.4 | 14.45 | 812 | +0.9 | |
| I | 37044.6 | 14.49 | 838 | +0.7 | |
| S | 37561.8 | 14.60 | 898 | +0.2 | |
| S | 37579.3 | 14.60 | 900 | +0.4 | |
| I | 37587.3 | 14.43 | 901 | -0.1 | |
| I | 37614.3 | 14.78 | 904 | +0.9 | |
| I | 37838.5 | 14.45 | 930 | +0.7 | |
| I | 37854.5 | 14.41 | 932 | -0.5 | |
| I | 37871.5 | 14.35 | 934 | -0.8 | |
| I | 37907.4 | 14.36 | 938 | +0.6 | |
| S | 38226.4 | 14.59 | 975 | +0.3 | |
| S | 38235.0 | 14.71 | 976 | +0.3 | |
| I | 38243.5 | 14.58 | 977 | +0.2 | |
| S | 38286.8 | 14.53 | 982 | +0.3 | |
| S | 38295.6 | 14.47 | 983 | +0.5 | |
| S | 38321.8 | 14.50 | 986 | +0.8 | : |
| S | 38372.2 | 14.40 | 992 | -0.6 | : |
| S | 38398.8 | 14.40 | 995 | +0.1 | : |
| S | 39383.2 | 14.40 | 1109 | +0.8 | : |
| S | 39685.8 | 14.20 | 1144 | +1.4 | : |
| S | 39763.4 | 14.40 | 1153 | +1.3 | : |
| I | 40030.5 | 14.35 | 1184 | +0.8 | |
| I | 42369.2 | 14.40 | 1455 | +1.1 | |
| I | 49511.6 | 14.07 | 2283 | -1.8 | |
| S | 49538.4 | 13.88 | 2286 | -0.8 | : |
| S | 49547.4 | 13.93 | 2287 | -0.4 | |
| S | 49840.2 | 14.04 | 2321 | -1.0 | |

detached systems, mass exchange, if occuring, does not much influence the period length. Though Evren (1989) shows that in the case of RT Lac an intermittent gas flow seems to exist between the binary components, additional quantities must be known to answer this question with more confidence. Hall (1972), for example, proposes that ejection of matter in regions of very strong starspot activity on one side of the cooler component may give large contributions to the changes in orbital period (rocket effect). Sahade & Wood (1978, on page 66) write that "the large period changes found in the RS CVn variables are still not well understood... and the energy required to eject larger amounts of mass must be very large". Other authors (e.g. Kopal 1978) state that it is difficult to estimate the mass loss. Nevertheless, Hall & Kreiner (1980) and Hall et al. (1980) tried to give crude estimates of the range of mass loss rates in 34 RS CVn-type stars based on the hypothetical assumptions of magnetic field strengths and further quantities. They got values up to about $10^{-6}$ $M_{\odot}$/yr in some extreme cases.

As already mentioned, the eclipsing minima in S 10947 occasionally disappear (see Figs. 2 and 3). Apart from S 10947 only very few binaries (none of which is a RS CVn star) are known to have occasionally vanishing eclipse amplitudes, and thus not much is known about their cause.

There are several possible explanations for varying eclipse amplitudes:

– *Triple system*: An obvious explanation of varying orbital period and eclipse depth is due to the influence of a third body in orbit (e.g. Africano & Wilson 1976). This possibility was later abandoned as a general explanation since (i) $O-C$ variations were actually observed in too many cataclysmic variables to attribute all to third bodies, and (ii) for the case of UX UMa the apparent sinusoidal $O-C$ variation was found not to repeat (Rubinstein et al. 1991). One exception is SS Lac which has ceased eclipsing completely. This is believed to be due to a change of the orbital inclination angle caused by a third stellar component which gives not only rise to an apsidal motion of probably $\sim$ 1000 years, but also to a periodic oscillation of the orbital inclination with a very long time scale (Milone et al. 2000, Torres & Stefanik 2000).

– *Dust obscuration*: Irregularities of production and destruction of carbon dust can hide the minima. As far as we know, this phenomenon primarily leads to small amplitude variations rather than a change of 0.5 mag as observed in S 10947.
– *Strong wind*: Variations of the accretion rate may easily affect variations in the amount of matter expelled by the system in a wind. As an example, the eclipsing binary CV Ser (not a RS CVn star) showed no eclipse light variations at all in 1970. According to Cowley et al. (1977) (see also Hoffmeister et al. 1984), it is not one of the stellar binary components which is eclipsed, but rather some bright material between the stars.

For S 10947, the short time scale and the non-periodic behaviour of the times of vanishing amplitude seem to rule out the influence of a third component. We therefore suppose that these eclipses are caused by circumstellar matter or changes in the accretion disk, variable in size and/or brightness. This supports earlier statements by Hall & Ramsey (1992) that extended matter in RS CVn systems may play a greater role than hitherto assumed.

## 3. Conclusions

Because of (1) the small difference to the best-fit X-ray position of only $\sim 5''$ (far below the X-ray position error), (2) the lack of any other optical objects within the X-ray error circle brighter than 19 mag. and (3) a X-ray-to-optical luminosity ratio of $L_{\rm X}/L_{\rm opt} \approx 0.01$ which is in the range exhibited by RS CVn stars, we are quite certain about the identification of RX J2009.8+1557 with S 10947 Aql.

S 10947 Aql shows interesting properties in its eclipsing light curve which may contribute to a better understanding of the RS CVn systems.

This work demonstrates the importance of plate archives where many still unknown secrets and information are hidden. Detailed spectroscopic observations are urgently needed to further the understanding of this enigmatic source S 10947 Aql. Also, continued long-term monitoring should determine the further evolution of the $O-C$ curve, and thus can prove/disprove the influence of a third body.

(1) The field photometry is based on two photometric nights in June 2000 with the Naval Observatory Flagstaff Station 1.0 m telescope. A Tektronix 1024*1024 CCD was used with Johnson-Cousins BVRI filters. Typical nightly zero point errors are less than 0.02 mag. Astrometry was performed with respect to USNO-A2.0 and has internal errors of less than 100 mas. The full calibration file including VRI measurements is electronically available from A. Henden at ftp://ftp.nofs.navy.mil/pub/outgoing/aah/sequence/j2009.dat.

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**Note added in proof:** Arne Henden, following our request in response to a suggestion of the referee, has performed a CCD-based photometric calibration as given below.

**Table 3.** Comparison stars

| Star position (2000)$^{(1)}$ | $m_{\rm pg}$ (mag) | $B$ (mag)$^{(1)}$ |
|---|---|---|
| $20^{\rm h}09^{\rm m}53\overset{\rm s}{.}92$ +15°57′07.″8 | 13.10±0.07 | 13.280±0.006 |
| $20^{\rm h}10^{\rm m}00\overset{\rm s}{.}63$ +15°57′02.″2 | 12.39±0.07 | 12.770±0.005 |
| $20^{\rm h}09^{\rm m}45\overset{\rm s}{.}25$ +15°56′52.″8 | 14.99±0.07 | 15.040±0.001 |
| $20^{\rm h}09^{\rm m}54\overset{\rm s}{.}54$ +15°55′44.″0 | 13.63±0.07 | 13.734±0.013 |