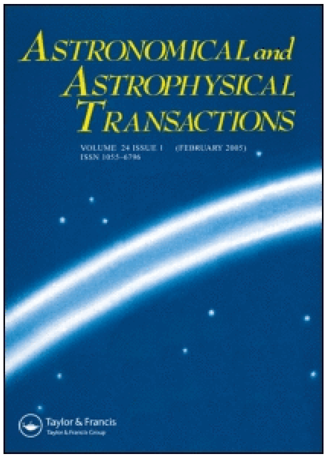

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 April 1998
To cite this Article: Pustylnik, I. (1998) 'The early history of resolving the Algol paradox', Astronomical & Astrophysical Transactions, 15:1, 357 - 362
To link to this article: DOI: 10.1080/10556799808201791
URL: http://dx.doi.org/10.1080/10556799808201791

Astronomical and Astrophysical Transactions, 1998,
Vol. 15, pp. 357–362
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THE EARLY HISTORY OF RESOLVING THE ALGOL PARADOX

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(Received June 7, 1996)

Scientific discoveries of great worth in 20th century astronomy have involved revolutionary ideas, technological breakthroughs and sometimes even changes in the dominating paradigm. Here we analyse briefly an early history of resolving the famous Algol paradox. We summarize multifold evidence suggesting that the Algol paradox posed a serious challenge to the 20th century physics of close binaries. It has been resolved by the collective efforts of a whole generation of astronomers rather than by anyone's individual ingenious accomplishment.

KEY WORDS Close binaries, Algol paradox

The amazing progress in understanding of the physics and evolution of close binary systems which we have witnessed in the second half of the 20th century raises many intriguing questions with no immediate answers. During the last 30 years the idea of the binary nature of various peculiar objects has enabled the elucidation, at least in their basic features, of the properties of such strikingly different, in their observable manifestations, double stars as cataclysmic variables, symbiotic and barium stars, X-ray bursters, binary radiopulsars, etc. The binary model remains at the top of the list of the most productive ideas invoked to explain the nature of elusive and mysterious γ ray bursts.

What may be equally amazing is the fact that inhabitants of a "cosmic zoo" of binary objects according to proposed evolutionary scenarios all have at least one key element, one crucial episode in their diversified history, which sounds nowadays almost like a cliche — *Roche lobe overflow.* A transparent physical idea of mass transfer driven on a thermal or even dynamical time-scale when a star in the course of its nuclear evolution fills its first critical Roche lobe revolutionized the whole discipline of close binary research. And this sends us back to the early history of resolving the Algol paradox in an attempt to trace the roots of subsequent spectacular achievements in this field.

As is well known, the Hertzsprung–Russell diagram was constructed at the very dawn of contemporary astrophysical research — 1910–1914. And although the verification of its genuine evolutionary nature took several decades, the cornerstone of the evolutionary concept (identification of the main-sequence stars, giant branch and white dwarfs) was laid down nearly 80 years ago. Curiously, as it may seem at first sight, even three decades ago the situation in the world of the physics of close binary systems looked completely different, at least to some investigators of double stars. According to the testimony of the well-known Soviet astronomer, from Leningrad, V. A. Krat a specialist in solar studies, and in eclipsing and spectroscopic binaries (Krat, 1962): "Successes of empirical-statistical works in stellar astronomy resulting in construction of spectrum–magnitude diagram, discovery of mass-luminosity and the period-luminosity law for cepheids have urged many investigators to look for correlations between various elements of close binary systems. Yet despite all efforts attempts to find such correlations proved to be futile... No new relations based upon statistical studies of close binary stars have been established!"

Whether Krat's judgement was fully shared by his contemporaries should not bother us much at this point.

For a number of years the crux of Algol-type secondary components remained one of the fundamental problems in the physics of close binary systems, a stumbling block for any comprehensive theory of stellar evolution. The most puzzling feature of Algol-type binaries widely known since Gerard Kuiper's pioneering investigation (Kuiper, 1941) lies in the fact that an early-type primary component (usually of B8–A5 spectral type) with a normal, for a main-sequence star, radius and luminosity is accompanied by a low-mass (ordinarily the mass ratio is $q \simeq 0.2$–0.3) companion with characteristics of a subgiant filling in its critical Roche lobe and having marked luminosity excesses (as large as 2–4 mag and even higher).

Because of the limited format of this contribution we enumerate only the basic ideas and technological developments which have dictated, in our view, the chain of subsequent events which culminated in J. Crawford's article (Crawford, 1955) and offered for the first time a key to the Algol paradox.

(1) In an early paper Chandrasekhar and Shoenberg (1942) (and Öpik in an even earlier, largely unnoticed article from 1938, for details see, for instance Öpik, 1977) indicated that after the hydrogen content in the stellar core during the course of nuclear evolution diminishes below 18% the core starts shrinking whereas the external layers will expand, i.e. a star climbs along the giant branch. In a close binary an invisible barrier exists in the form of the Roche lobe which a star being in a state of static equilibrium cannot surpass.

(2) Even before the spectacular successes of stellar spectroscopy it had been firmly established that components of close binaries lose mass at a rate of 10^{-8}–$10^{-5} M_{\odot}\ \mathrm{yr}^{-1}$ which on one hand implied their swift evolution and on the other, necessitated a due account of the influence of circumstellar matter upon both the radial velocity curves and the light curves (see, for instance, the monograph *"Evolution of Stars"*, Struve, 1950).

(3) A quick proliferation of phototubes during the 1940s–1950s even in small observatories (following Kron, 1958, a small telescope equipped with an electrophotometer is "like a Napoleon, small in size but large in accomplishment").

The introduction of photoelectric photometry (which raised the accuracy of observations up to 0.002–0.005 mag) enabled among other things measurement of the apsidal motion for a dozen binaries thereby for the first time firmly establishing a very high central concentration degree of matter in stars. This observational result in its turn has transformed the Roche lobe model from a beautiful abstract notion into a powerful tool for probing stellar interiors and binary evolution.

(4) The challenge of the considerably increased precision in fixing the light curves of eclipsing binaries has been met by theoreticians (notably by Russell and Merrill in the USA, and Martynov, Krat, Tsesevitch and their collaborators in the USSR) who elaborated effective techniques to account for various proximity effects shaping the light curves of eclipsing binaries whereas Kopal worked out his elegant analytical methods for the purpose of accurate measurements of the various Roche lobe parameters.

(5) Thus, due to innovations in optical instrumentation and receivers, to the concerted efforts of both observers and theoreticians data of a quality unrivalled in any other branch of stellar astrophysics — masses, luminosities, effective temperatures, radii of hitherto unattained accuracy started to accumulate for the components of Algol-type binaries (though the accuracy of the data on the masses and luminosities for the secondary components still remained unsatisfactory for many years).

It seems appropriate to remember at this point that close binaries provide us with a unique opportunity of tracing the effects of differential evolution of stars of virtually the same age and initial composition which may differ in initial mass. And for this one needs a statistically representative sample of objects with accurately measured M, L, R, $T_{\rm eff}$. Apparently Parenago and Massevich (1950) were the first to gain the fruits of such a statistical approach. They compiled a catalogue which included quite reliable absolute parameters for a dozen Algol-type binary systems. Having failed to locate the positions of subgiants on an L–M diagram (because of the enormous scatter of the observed points) they inferred that there are no single $L \sim M$ and $R \sim M$ relations valid for the secondary components of Algol-type binaries. But having experimented with two parameter relations they found that relations of the type $L = f_1(\lambda, M)$, $R = f_2(\lambda, M)$ nicely reproduce the observed points with subgiants forming a distinct sequence and λ being yet some unspecified parameter. Struve (for details see Struve, 1954), an observational astronomer of great experience endowed with uncommon intuition guessed that the mysterious parameter λ introduced by Parenago and Massevich is nothing else but the mass ratio of the components q and proved this by plotting the diagram $\Delta(M - L) \sim q$ (where $\Delta(M - L)$ stands for the departures of the mass–luminosity relations observed for subgiants from the theoretical one for main-sequence stars) and inserting observational points corresponding to a dozen well-studied Algol type binaries. Yet standing only one small step from solving the Algol paradox (because *a posteriori* we know or rather believe we *do know* that the diagram $\Delta(M-$

$L) \sim q$ first plotted by Struve has direct evolutionary implications, i.e. we should see in it the binary systems caught at different ages following the crucial mass transfer episode). Struve looked in the wrong direction. Large luminosity excesses observed in subgiants he ascribed to initial enrichment by the dust particles at the early stage of contraction of "subsidary condensations", in other words, the progenitors of subgiants. Being dissatisfied with his own results, yet at the same time being aware of the fundamental implications of the Algol paradox from the evolutionary viewpoint Struve recommended John Crawford to reinvestigate the problem (see Crawford, 1955). It would be perhaps too difficult to speculate over the reasons why Struve overlooked Crawford's explanation of the Algol paradox (after all, Crawford used in his article the same data from Parenago and Massevich and the plot $\Delta(M - L) \sim q$, to which he added his own observation that subgiants fill in their respective Roche lobes, a fact certainly known by that time by Kopal). In retrospect it would be interesting to know more about the attitude towards the problem of Algol paradox of those involved in its resolution. However, in a book *Astronomy of the 20th century* by Struve and Zebergs which appeared in 1962 the reader will not find a single word about the Algol paradox. In *Elementary Astronomy*, (Struve *et al.*, 1959) published earlier the hypothesis of Roche lobe overflow is briefly discussed and both the names of the Crawford and Kopal are mentioned. One should not forget that Struve died in 1963 and was seriously ill for some time before that (A. Batten, 1996, private communication). Kopal, the man who has done more than anyone else to investigate the various properties of the Roche model, in 1971 wrote the following lines (for more details see Kopal,1971): "The present author pointed out many years ago (Kopal, 1955) that there exists indeed a distinct group of eclipsing variables (which we called the "semi-detached systems") in which one component has indubitably attained the Roche limit — but, unfortunately for our expectations, it is the wrong star! For the most striking feature of such semi-detached systems is the fact that... it is *the less massive component which appears to be at its Roche limit, while its more massive mate remains well interior to it.* This fact, which has since earned the epithet of an "evolutionary paradox" has been with us now for more than 15 years and continues to remain a paradox;... "and still further..." However, other aspects which remain yet to be investigated are so many that a considerable amount of work must be done before more detailed comparisons between theory and observations can possess much meaning."

It is worth remembering that this opinion was voiced long after Morton (1960) and Smak (1962) provided convincing arguments showing that a binary system will survive a process of mass transfer in which an exchange of the roles of the two components occurs on the Kelvin time-scale so that only a few, if any, stars can be caught in the act in the samples we have at our disposal. As one can see from Kopal's just quoted article he was quite familiar also with the extensive theoretical work done by Plavec, Paczynski, Kippenhahn and their collaborators (though apparently he was unaware of an original article of Sniezhko (1967) from the same period) who by that time had made detailed and extensive calculations of evolutionary sequences following the Roche lobe overflow for a star being on a main-sequence (case A), reaching a giant branch (case B) and finally for a supergiant evolutionary stage (case C) (see, for instance, Plavec, 1970).

Although the criticism of these efforts by Kopal seems to be unduly harsh some of his comments sound today as prophetic: in many cases it appears more plausible that magnetic stellar wind rather than evolutionary expansion may cause both mass loss and mass transfer following Roche lobe overflow (see, for instance, Iben and Livio, 1993, or Tout and Hall, 1991).

Summarizing our brief discussion of the early history of resolving the Algol paradox can one state with confidence that this problem at least by now, at the turn of the second millenium, is behind us? According to Batten "It is fair to say that there is a consensus that close binary systems evolve by transfer of mass from one component to another (and out of the system) and that in the systems like RW Tau we *may* be witnessing a late stage of this process, while in β Lyr... we perhaps see a somewhat earlier stage. It is also fair to recall that the consensus is challenged (Kopal, 1978). All of us must hope that this argument will be settled during the next 100 years, once and for all. Astronomy, being an observational science, rarely if ever provides us with an *experimentum crucis*; but definite proof that in systems like RW Tau we can see material that has been through the carbon–nitrogen cycle would come close to playing the role of such an experiment." (Batten, 1988).

The most recent studies of the effects of chemical evolution in Algols (see, for instance, the article of Sarna and De Greve, 1996) seem to agree favourably with the theoretical predictions at least for carbon to hydrogen abundances though much more observational material will be needed before the definitive answer to this tantalizing problem will be obtained.

If the history of resolving the Algol paradox teaches us anything then one can envision that proliferation of a new generation of CCD cameras will open up new horizons in Algol binary research on an extragalactic scale. The first steps in this direction have already been made. I refer to recently published discoveries of many dozens of eclipsing binaries in open stellar clusters (for details, see the paper by Mazur *et al.*, 1955).

Acknowledgements

The author is indebted to Professor A. Batten for carefully reading the manuscript and making many helpful critical remarks, to Professor A. M. Cherepashchuck for stimulating discussions and to Dr U. Veismann for useful information on the introduction of new astronomical receivers prior to and during the second World War.

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