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Abstract. The Algol paradox posed a serious challenge to the theory of evolution of close binaries. We indicate that it has been resolved by the collective efforts of a whole generation of astronomers rather than by anyone's individual ingenious accomplishment. We discuss the role of illuminating ideas put forward by Zdeněk Kopal in solving the Algol paradox.

Keywords: history – close binaries, evolution

1. Introduction

The amazing progress in understanding of the physics and evolution of close binary systems which we have witnessed in the second half of 20th century raises many intriguing questions with no immediate answers. During the last 30 years the idea of a binary nature of various peculiar objects enabled the elucidation, at least in its 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 radio pulsars etc. The binary model remains on top of the list of the most productive ideas invoked to explain the nature of elusive and mysterious \(\gamma\)-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 cliché – Roche lobe overflow. A transparent physical idea of mass transfer driven on a thermal or even dynamical time scale, when a star in course of its nuclear evolution fills in 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. It would be tempting to look at the whole issue of Algol paradox in a broad historical prospective making use of a rich stock of knowledge accumulated during the later half of the century separating us from pioneering investigations of Struve (1954), Parenago and Massевич (1950), Crawford (1955), Hoyle (1955), and Kopal (1971). Although from time to time I will attempt to place some aspects of the problem of the Algol paradox into a modern prospective, it will be done mostly for illustrative purposes or in order to compare
2. Resolving the Algol Paradox

The Algol paradox has been the subject of numerous articles and manuals and it makes no sense to elaborate them in length. It suffices to say that the 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 radius and luminosity normal for a main sequence star is accompanied by a low-mass companion (ordinarily the mass ratio is $q \simeq 0.2–0.3$) with characteristics of a subgiant having marked radius and luminosity excesses (as large as $2^m–4^m$ and even higher).

Although this paradox dates back to the early forties of the 20th century and is associated with the pioneering investigation of Gerard Kuiper, it became especially acute in the early fifties due to advancements of stellar evolution investigations, a rapid progress both in a theory of eclipsing binaries and in stellar photometry. Specifically a proliferation of phototubes and photomultipliers and their low prices made them commercially available even for small and modestly equipped observatories, like Odessa observatory in Ukraine or Tartu Observatory in Estonia where I started my scientific career. I recall how proud was my teacher and supervisor unforgettable Professor V.P. Tsesevich, a former director of Odessa observatory, when he came back from one of his first duty trips behind the iron curtain and ventured to bring in his pocket a small phototube manufactured in UK (in the full swing of the cold war phototubes were proclaimed to be strategic articles prohibited for sale in Soviet block countries).

Application of photomultipliers for the needs of a broad-band photometry of variable stars (following Kron (Kron, 1958) a small telescope equipped with electrophotometer is like a Napoleon, small in size but large in accomplishment) meant a quality change in observations of eclipsing binaries. Introduction of photoelectric photometry (which raised the accuracy of observations up to $0.002^m–0.005^m$) enabled us among other things to measure the apsidal motion for a dozen of binaries.

According to the classical theory of apsidal motion in binary systems (first elaborated by Russell in 1928 and later on improved by Chandrasekhar, Stern, Žópal, Martynov and others), the ratio of a full period of apsidal motion $T_{aps}$ to the orbital period $P_{orb}$ obeys in the first approximation a fairly simple elation

$$P_{orb}/U_{aps} = \Sigma_{i=1}^{n} k_i r_i^5 (M_3 - i/M_1) F(e),$$

(1)
\( k \) are determined by the density distribution inside the component stars (to be more specific, by the ratio of the running density of matter to its average value), so that the value of parameter \( k \) ranges between 0.75 for a completely homogeneous star and 0 for a point mass, i.e. for the Roche model. Prior to the World War II debates around the possible values of the parameter \( k \) still gave no definitive outcome. The measured effect is indeed very subtle, and nature is not quick in cooperating with astronomers to reveal the presence of apsidal motion for many reasons. The apsidal motion manifests itself in the variable displacement of the moment of the secondary minimum from the moment of conjunction, when normally the low-mass component will be eclipsed. But it is not an easy task to measure reliably the effect. Interaction effects between the components (like reflection effect, surface activity, circumstellar matter) considerably influence the shape of the light curve. Also the amplitude of the secondary minimum is small (typically \( \leq 0.05 \)), and finally the displacement of the moment of minimum is proportional to the product \( e \cos \omega \) (\( e \) being the eccentricity of orbit and \( \omega \) the longitude of the ascending node of the orbit).

Thus, we practically miss the systems whose orbits are unfortunately inclined to the earth-bound observer. That is why it took a lot of effort in the mid-fifties analyzing available observational series before for the first time it was firmly established a remarkably high degree of concentration of matter towards center for a dozen of eclipsing variables, yielding the values \( k \approx 10^{-3} - 10^{-2} \). This observational result has transformed the Roche model from a beautiful abstract notion into a powerful tool of probing stellar interiors and binary evolution.

Apparently Parenago and Masseevich (1950) were the first to gain the fruits of a true statistical approach based on improved observational data. They compiled a catalog which included quite reliable absolute parameters for a dozen of Algol-type binary systems. Having failed in locating the position of subgiants in the L-M diagram (because of an 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 \( L = f_1(\lambda, M) \), \( R = f_2(\lambda, M) \) nicely reproduce the observed points with subgiants forming a distinct sequence and \( \lambda \) being yet some unspecified parameter. Otto Struve, an observational astronomer of great experience endowed with uncommon intuition, guessed that the mysterious parameter \( \lambda \) introduced by Parenago and Masseevich is nothing else but the mass ratio of the components \( q \) and proved that by plotting the diagram \( \Delta M \sim q \) (where \( \Delta M \) stands for the luminosity excesses observed for subgiants from the theoretical one for main sequence stars) and inserting observational points corresponding to a dozen of well-studied Algol-type binaries (Struve, 1954) (see Figure 1).

And yet, standing only one small step from solving the Algol paradox (because \textit{a posteriori} we know that the diagram \( \Delta M \sim q \)) first plotted by Struve has direct evolutionary implications, i.e. we should see in it the binary systems caught at
Figure 1. The diagram luminosity excesses $\Delta M$ for subgiants relative to main sequence stars in Algol-type binaries versus mass ratio $M_1/M_2$. This diagram has been constructed for the first time by Struve (1954).

Different ages following the crucial mass transfer episode, Struve looked in the wrong direction. He ascribed large luminosity excesses observed in subgiants to initial enrichment by dust particles at the early stage of contraction of "subsidiary 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 re-investigate the problem (Crawford, 1955). It would be perhaps too hazardous 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 $\Delta M \sim q$, to which he added his own observation that subgiants fill their respective Roche lobes, a fact certainly known by that time to Kopal (Kopal, 1955).
nosity and radius excesses observed in subgiant secondary components in Algol-type binaries. For unclear reasons this paper of Hoyle remained unnoticed for many years. It seems to be appropriate to cite at this point a fragment from a private letter to the present author by Prof. Alan Batten (Batten, 1988) without any comment:

I am myself uncertain how far Hoyle stumbled on the same idea independently. In his book “Frontiers of Astronomy” (published 1955, the same year as Crawford’s paper) on pp. 195–202 he gives a very good account of mass-transfer, including a good approximation of the track of the mass-losing component in the H–R diagram. I know that Struve discussed Crawford’s work at a Liege symposium a year or two earlier, at which Hoyle was present. I have always assumed that Hoyle had assess to an advance copy of Crawford’s paper and was popularizing that. When I recently read his autobiogaphy, however, I realized that his own work on stellar accretion would have got him close to the idea of mass-transfer. Because I have been asked to consider writing another book on binaries, I may write him and ask him whether or not he got the idea independently.

Kopal, the man who has done more than anyone else for investigating 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—in every single case known to us so far—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; for in spite of a large amount of work towards its clarification it is not yet satisfactorily understood.

and still further

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.

So what’s the point, why the dissident opinion of Kopal on the Algol paradox should deserve a special discussion? The main purpose of my presentation is to convince the reader that in actuality, notwithstanding all rhetoric, Kopal has done, perhaps, more than anyone else for the resolution of the Algol paradox. Pardon my
Sirius B or Procyon B must once have been more massive than their principal components—probably very much more so judging from their large disparity on evolutionary stage ... A transfer of mass across so great a gap of space would require extremely special initial conditions of ejection which are most unlikely to be met. Much more probable is the view that in such systems, mass was lost by ejection with velocities well in excess of that of escape from the gravitational field of the binary; and if so, a mechanism which can accomplish this could have done the same to more orthodox binaries whose secondary components are to the right—instead of the left—of the main sequence in the H-R diagram.

To sum up Kopal’s statements, as long as the just mentioned uneasy aspects are not addressed in a rigorous way, it is too premature to announce that the Algol paradox is resolved (it is noteworthy that Kopal enters here into polemics with Plavec whose review paper on evolution of close binaries was published in the previous volume of the “Publications of Astronomical Society of the Pacific” (Plavec, 1970).

Among the critical arguments of Kopal only one can be relatively easily dismissed. Concerning the lack of binaries with nearly equal masses of the components, it seems that this is an ideal illustration of a well-known aphorism: “the lack of evidence is not the evidence of the lack”. In other words, if we recall such bizarre systems like W Ser with extremely peculiar behavior of the their light curves (see, for instance, Guinan, 1989) and assume that there may be a vast amount of similar systems with rather small inclination angles, will we be able to identify adequately such binaries if they are caught in a phase of rapid mass loss and mass transfer?

Now what is absolutely remarkable in my opinion about other remaining difficult issues of the Algol paradox where Kopal is reluctant to compromise or accept the conventional wisdom of his epoch is the fact that exactly a study, tackling the problems explicitly named in Kopal’s article from 1971, became a mainstream of research in physics and evolution of close binaries in the last quarter of the 20th century. In all probability, this will be an intriguing subject of investigation for a historian of astronomy who will clarify one day to what extent the ideas of Kopal fermented discussion of open issues or even predestined subsequent progress in evolutionary studies of close binary systems. My task is more modest, also the format of my presentation leaves little space for in-depth analysis, so my discussion is confined just to several theses:

- in fact by the time of publication of the article in question the combined effect of the mass and angular transfer along with the accompanying changes of the Roche lobes sizes tracing momentary variations in mass ratio was treated properly by a young Soviet researcher L. Sniezhko (Sniezhko, 1967) from Ural University, but as you know, the contacts of Soviet astronomers with their Western colleagues at that time were episodic,
- the complicated problem of mass loss and mass transfer is of course multi-faceted and deserves a dedicated and detailed treatment. For the time being it is suffice
to say that in the middle seventies Bogdan Paczynski with his associates invoked an idea of a common envelope, which proved to be instrumental in explaining another paradox of binary evolution, exactly the one concerning the occurrence of white dwarfs in Procyon and Sirius so prominent in critical discourse quoted above in the current report (Paczynski, 1971, 1976). Apropos, Paczynski in his pioneering article dedicated to this problem directly refers to Kopal’s article.

-- it is symptomatic that at the very end of Chapter 6 of his biographical book “Ol Stars and Men” Kopal (1986) writes among other things the following lines:

...it has traditionally been assumed so far that the fractional dimensions of the components of close binary systems remain significantly constant over thousands, or tens of thousands of orbital cycles. But although such components may indeed remain in the state of equilibrium, they may oscillate about it with frequency depending on their internal structure; and if so, the ratio of their radii would not remain constant but oscillate with periods comparable with that of their orbit. Moreover, if – as is more than likely – the orbital period of the system is not commensurable with those of free oscillations, photometric beat phenomena will arise which make the shape of the light curve not repetitive from cycle to cycle. ... A theory of the photometric consequences of such oscillations has also been developed to a certain point (cf Kopal, 1982); but its application to practical cases still constitutes a task for the (albeit near) future.

Here we have another example of Kopal’s very keen insight into the immediate future trends in close binary research.

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 millennium, is behind us? According to Batten (1988)

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.

The most recent studies of the effects of chemical evolution in Algols (see, for instance, Sarna and De Greve, 1996) seem to agree favorably 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.
3. Conclusions

- Algol paradox posed a serious challenge to the theory of evolution 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.
- One should not necessarily identify the author with his brainchild. Once the latter is perpetuated, be it a published book, patent or a technological novelty, it starts its own life. If we measure a scientific legacy of an individual scholar not that much by his own words but rather by his real impact on future advancements of research, the fundamental role of Kopal in resolving the Algol paradox can hardly be overestimated.

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References