TWO CENTURIES OF STUDY OF ALGOL SYSTEMS

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ABSTRACT. The periodicity of the light variation of Algol, discovered just over 200 years ago, may be regarded as the beginning of the study of eclipsing binary systems, especially those of the Algol type. Such studies, however, gained no real momentum until Vogel, 100 years ago, demonstrated by spectroscopy that the binary hypothesis of Algol's light changes is, in its essentials, correct. Three elements were needed to give us our modern notions of evolution by mass-transfer, namely: (i) results of combined analysis of light-curves and velocity-curves, (ii) evidence of circumstellar matter within binary systems and (iii) the notion that at least one component of an Algol system was near the limit of dynamical stability. All three entered the literature within about a decade, approximately halfway through the second century of eclipsing-binary studies; but it is the computational and instrumental developments of the last 25 years that have made real progress possible. We still lack commensurate theoretical developments, and the whole question of the contribution of Algol systems to the development of the Galaxy has barely been considered.

1. INTRODUCTION

I have been asked to prepare an historical introduction to this colloquium that will lead directly into discussion of the most modern problems posed by Algol-type systems. This is a challenging assignment to which I am not sure that I am equal. I am relieved of the need to discuss what might be called the prehistory of the subject - the question whether or not the names given to Algol itself in many cultures (but especially by the Arabs) indicate a knowledge of the variability of its light - by a recent paper published by Budding (1988) - see also Van Gent (this colloquium). As far as _we_ know, the variability was discovered by Montanari in 1670. That discovery has been thoroughly documented by Kopal (1959), and no-one who is not prepared to spend considerable time - without any guarantee of ultimate success - in the libraries of Europe's oldest universities, can hope to unearth further details or possible earlier observations. Rather than

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indulge in pointless speculation, I shall immediately identify Goodricke's (1782 - but published 1783) discovery of the periodicity in Algol's light variation, together with his accurate determination of the period, as the beginning of the history of our subject. One member of our organizing committee had, indeed, suggested an I.A.U. colloquium to mark the 200th anniversary of Goodricke's discovery, but he underestimated the necessary lead-time. We are only six years late, and we may reasonably celebrate, in these pages, two centuries of study of Algol-type systems.

2. THE CENTURY OF DISCOVERY

Goodricke's discovery has also been documented by Kopal (1959), although Hoskin (1979) has questioned whether it and the binary hypothesis were entirely Goodricke's, or (at least partly) the work of his collaborator and relative Edward Fairfax Pigott. The matter is not of great importance in our context; the relevant papers were published over Goodricke's name. More to the point, I believe, is that the binary hypothesis is not quite the brilliant insight of a lone young worker (whether Goodricke or Pigott) that it is sometimes represented to be. Michell (1767) had advanced his statistical arguments that many of the stellar pairs seen through telescopes must be what Herschel was later to call binary systems, and Herschel himself began his catalogues of double stars at about the same time as Goodricke's work. According to Aitken (1935), C. Mayer (1779) had published speculations on satellites of other stars and provided Bode with a list of known doubles, which the latter published in 1781 (in his Jahrbuch for 1784). Pigott and Goodricke were almost certainly familiar with these works, and were climbing on a band-wagon as surely as did those who, a decade or so ago, saw a black hole at the heart of every unusual phenomenon. In some ways, the more original of the two hypotheses advanced in Goodricke's paper was that of a spotted star (Hoskin believes that Goodricke may have preferred it). As is well known, that hypothesis has been resurrected to explain the phenomena of the RS CVn systems, which will certainly figure in this colloquium as systems related to Algol - so both of Goodricke's ideas will be discussed in the papers that follow.

Progress in the first century of the study of Algol systems was slow, the next major landmark being Vogel's (1889) discovery of the radial-velocity variations of Algol. Until then, the eclipse hypothesis seems not to have been fully accepted, although it was obviously the most likely explanation of the light changes observed in Algol systems. Eggen (1957) has drawn attention to a previously unpublished manuscript, written a few years after Goodricke's paper and clearly stimulated by it, which develops the eclipse hypothesis.* The

* I am indebted to R.H. van Gent for drawing my attention to more detailed publication by D. Huber in 1787 which has been described by E. Zinners in Astronomie-Geschichte ihrer Probleme (Verlag Karl Albert, Frieburg-München 1950) pp. 347-349.

nineteenth century was also a period in which the number of known variable stars (including what we now call eclipsing variables) slowly but steadily increased - primarily through the work of Argelander, who devised their nomenclature. Many of the best-known Algol systems have single-letter designations: U Cephei, U Sagittae, U Coronae Borealis, R Canis Majoris, S Cancri, S Equulei. These names are evidence of the early discovery of the variability of these stars. As Plavec (1973) reminded us at the last I.A.U. meeting on binaries that was held on this island, observational selection strongly favours the discovery of Algol systems. This is true, whatever the origin of these binaries, or the explanation of the phenomena we observe in them. The chief reason we are holding this meeting is that Nature has made Algol systems easy to discover.

Vogel's radial-velocity measurements were hailed as "strong support" for the eclipse hypothesis, which has scarcely been seriously questioned since, and must now surely be taken as an established fact. His work marked the end of the first century of Algol studies and helped to stimulate the development and application of methods of light-curve analysis, which were to prove so important in the second.

3. THE CENTURY OF PUZZLING ACHIEVEMENTS

At first, spectroscopy and photometry complemented each other, until Carpenter (1930) obtained a velocity-curve for U Cephei that indicated a large orbital eccentricity for a system whose light-curve (Dugan 1920) clearly indicated a circular orbit. This notorious exception was largely ignored until Struve showed, a decade later, that it was by no means an isolated case. It appears to have been due to the influence of H.N. Russell that Carpenter's paper was first ignored. Russell was (rightly) convinced that the light-curve was the more trustworthy, but failed to understand that the distortion of the velocity-curve was an important clue to the nature of the system. Carpenter's work provided one of the elements needed for modern ideas of Algol systems to develop, namely, the combination of photometric and spectroscopic observations in such a way as to demonstrate that at least one of them is systematically affected by factors not directly connected with orbital motion. At about the same time Walter (1931) had provided another element by pointing out that the secondaries in Algol systems were near the limit of dynamical stability. In retrospect, if someone had put these two ideas together when they were first published, we could have had something very like the modern theory of Algol systems about twenty years earlier than we did. The ideas were not put together, partly because of the mistrust of Carpenter's work, partly because Walter believed Algol systems to contain young (pre-main-sequence) stars, and perhaps partly because North American scientists, even in those days, did not read European papers - especially those not written in English. Kopal's citations, rather than Struve's, have saved Walter's work from oblivion. The modern study of Algol systems can be dated from the publication, in consecutive years, of these two papers, although progress was delayed while the energies of the world were absorbed by more pressing matters. Even so, Joy (1942) was able to provide the third element that, historically, was needed for the development of modern ideas - the demonstration that circumstellar matter exists in Algol systems. I have discussed the significance and consequences of this work so recently (Batten 1988) that I cannot add anything new now. I will repeat, however, that the historical importance of Joy's observations, as a stimulus to Struve, is clearly demonstrated by the latter's many citations of them.

In just over a decade, therefore, three important papers were published that were both the results of achievement and the genesis of puzzles. Struve first put together the clues provided by Carpenter and Joy and, in doing so, rediscovered Walter's idea that the secondaries were near the limit of stability, but he now correctly identified them as evolved stars. Wood (1950) emphasized again the near instability of the secondary components of Algol systems, attempting to link this fact to the period changes so characteristic of them, helping to stimulate some important work by the Polish school (Kruszewski 1964) Crawford (1955) and Hoyle (1955) introduced the important notion of mass-transfer. Kopal (1957) introduced more rigour into the discussion by relating the instability more closely to the relationship between the surfaces of the binary components and the Roche equipotentials, first described (in the context of binary stars) by Kuiper (1941). It is not necessary, however, to review yet again these developments or the early calculations of mass-transfer. Many reviews have been published (e.g. Plavec 1970, Kopal 1971, Paczynski 1971, Batten 1981, 1988) and the story is well-known to most participants in this colloquium. I want rather to focus attention on the central hypothesis that will be assumed by most of us: that the systems we now observe were produced by mass-transfer and mass-loss through gas streams and disks whose presence is shown by effects that we can still see. There is so much evidence - spectroscopic, photometric, polarimetric and radio - for such streams in Algol systems that we cannot ignore it; but we have all found it very difficult to construct any detailed map of the distribution of densities, temperatures and velocities within that circumstellar medium. Some progress is being made by spectroscopy with high time-resolution and perhaps by Doppler imaging, but I believe that the general problem is insoluble unless some plausible model is first assumed. We cannot exmaine a detailed line profile (say Hα in the spectrum of U Cephei) and ascribe each feature in it to this or that stream. Struve was guilty of gross oversimplification of this kind, at least in his early work, but that is often the only way to make progress. Similarly, at the theoretical level, we can only guess the relative importance of gravitational, eruptive and magnetic forces. It is these uncertainties that give rise to controversy in our work. We need to know the mechanism of mass-transfer, and do not. Kopal's (1978) criticisms are aimed at the Achilles' heel of of our theory. The situation resembles that found in geophysics when the idea of continental drift was first becoming an acceptable scientific hypothesis. Jeffreys (1964) criticized his colleagues quite strongly for rushing to embrace the idea of a drift for which, at that time, no adequate mechanism had been proposed. A geophysicist friend whom I consulted said that Jeffreys was undoubtedly right, but the explanatory power of the theory was so great that most geophysicists willingly accepted it. We are in much the same position: there is no good theory of the Algol systems, but just an heuristic description. We will probably have to iterate between theory and observation and we may never be able to answer completely the demand for a demonstrably unique model. This, however, is the area in which study is most urgently needed. Computing capabilities have been improved so much recently, that it must surely be possible to improve on the pioneering work of Prendergast and Taam (1974), Biermann (1971) and Lubow and Shu (1975). We need to convince theoreticians that the problems posed by Algol binaries are important.

The prime achievement of the second century of research on Algols has been the realization that components of binaries, if they are close enough to each other, do affect each other's evolution, and not only Algols, but probably a wide variety of binaries with unusual characteristics, can be exaplined in this way. Another has been the derivation of reliable dimensions for many of the systems. The puzzles are still many. We do not know exactly how an Algol system is formed, how much mass is transferred and how much lost to the system. Nor do we know exactly how the mass that is transferred passes from one star to another. We have not fully and convincingly related the period changes we observe to the evolution of the systems themselves. These are some of the problems to which we need to direct our attention in the years to come.

4. ARE ALGOLS IMPORTANT?

Until now, I have not defined an Algol system, partly because the scientific organizing committee did not want to waste time on arguments about definitions. It is good, however, to have some idea what we are talking about and I offer the following response I recently made to a challenge to define Algol systems in one sentence: a binary in which the less massive stellar component fills its Roche lobe and the other, which does not, is not degenerate. I shall be interested to see if any better definition emerges from this colloquium. Some would like to make it more specific, but I do not think the definition admits anything that we would not class as an Algol (except possibly some symbiotic stars), and it certainly excludes cataclysmic variables. It is also a purely descriptive definition, in no way prejudging the past history of such systems, or the interpretation of the phenomea that most of us ascribe to gas-streams. The definition does indirectly draw attention to the evolutionary paradox that lies at the root of the interest that Algol systems possess for us here.

Many of us are aware, however, that not all our colleagues share our enthusiasm, and some of them appear to regard the problems of Algol systems as unrelated to the development of the Galaxy itself, which has now become one of the most fashionable areas of research. This is largely our own fault, because there has been a "missing factor" in our research on Algol systems. You will find very little in the literature on the space density or galactic distribution of Algol-type binaries. Statistical compilations, such as those by Giuricin *et al*. (1983) or Budding (1984) are more concerned with the properties of individual systems (periods, eccentricities etc.) than with the properties of the whole population. Yet for some time now we have all accepted that mass-transfer is not conservative, both because conservative calculations do not reproduce the more accurate masses, luminosities and radii now available - as already adumbrated by Plavec (1973) - and because observations in the ultraviolet (e.g. Kondo, McCluskey and Stencel 1980) provide direct evidence of mass-loss from Algol systems. Now there is also evidence that material that has been transferred from one component of an Algol system shows anomalous abundances in the sense (carbon-poor and nitrogen-rich) that would be expected if the layers of the mass-losing star in which the C-N-O cycle has been operating have been exposed (Plavec 1983, Parthasarathy, Lambert and Tomkin 1983). The interpretation of this evidence may be a subject for discussion at this colloquium, but let us grant for a moment that it *does* indicate anomalous abundances. We must then deduce that much of the matter lost to the system is similarly changed in composition and is helping to modify that of the interstellar medium. How important are Algol systems, in this respect compared with supernovae and other cataclysmic variables? A geophysical analogy may be helpful again. Are the rare but spectacular explosions like that of Mt. St. Helens more important in modifying the earth's atmosphere than the slow but virtually continuous out-gassing of geysers like Old Faithful? Of course, Mt. St. Helens put vast clouds of dust and ash in the atmosphere that never come from Old Faithful - the two things are *qualitatively* different, but the answer to the quantitative question is not obvious. Similarly, supernovae enrich the interstellar medium with heavy elements in a way that Algol systems cannot, but the quantitative answer is again not obvious. The matter is not discussed at all in standard reviews on the chemical evolution of the Galaxy (Audouze and Tinsley 1976, Tinsley 1980) although, to be fair, most students of Algols were not then drawing the question to the attention of colleagues in other fields. The only attempt to deal with the question that I have found is a very brief discussion by Giuricin, Mardirossian and Mezzetti (1983) who conclude that Algol-type systems may be responsible for between five per cent and twenty per cent of all the matter returned by stars to the interstellar medium. Their discussion of the point is so condensed that it is hard to assess their result and their conclusion that the contribution of Algols is small seems odd, if that contribution should be as high as twenty per cent. The question needs further study.

One obvious starting point is precisely to try to determine the space-density of Algols. A rough estimate, for our immediate neighbourhood, can be made by considering the bright Algol systems for which parallaxes are known - e.g. Algol itself, δ Librae and possibly δ Capricorni, which are at distances of 22, 50 and 11.5 parcsecs respectively. (The other bright Algol, λ Tauri, is appreciably more luminous and more distant.) These figures suggest a lower limit of one

Algol in every 175,000 cubic parsecs (about 6 x 10^{-6} psc^{-3}). There must, of course, be non-eclipsing Algols, not recognized as such. The ratio of non-eclipsing to eclipsing systems depends on what is supposed for the limiting inclination to produce eclipses - the ratio is hardly likely to exceed ten, and we can probably take a rough working figure of 10^{-5} Algols psc^{-3}. By a similar argument, based on the nearest known cataclysmic variable, Garrison *et al.* (1984) find a space density for those variables of 1.3 x 10^{-6} psc^{-3}. On the face of it, Algols are about ten times as numerous, in the immediate solar neighbourhood, as cataclysmic variables. No far-reaching conclusions should be drawn from this figure, however, since the derivation is open to the objections that it is based on samples that are small and probably incomplete and I am aware of unpublished work which may remove δ Capricorni from consideration as a possible Algol. The figure is presented, rather, as an indication of a line of research that has been neglected and ought to be pursued. Nevertheless, it does suggest that Algols may be more important than ordinary novae in replenishing and modifying the interstellar medium.

Up to a decade or so ago, period-changes drew a lot of attention since they seemed to offer a useful clue to the nature of Algols. Indeed, I still believe the accumulation of data on this subject to be necessary. In the last two decades, calculations of mass-transfer models have been significant (despite the sometimes artificial assumptions on which they were based) and stimulated many of the observations discussed here. I believe that a new stimulus to our studies may come from a consideration of Algols as a sub-population of the Galaxy, and the relation of this sub-population to others. Such work should convince our colleagues that Algols are important, quite apart from their intrinsic interest for us, and it may provide the clues we need to enable some reviewer a hundred years from now to describe the third century of Algol studies as "The Century of Understanding".

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